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ON SOLAR ECONOMICS

AUTHOR(S): Shaul Ben-David, UNM
Scott Noll, UNM
Fred Roach, LASL
William Schulze, USC

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IMPACTS OF THE NATIONAL ENERGY
PROGRAMME ON SOLAR ECONOMICS[§]

F. Roach
Los Alamos Scientific Laboratory
Los Alamos, New Mexico U.S.A.

S. Ben-David and S. Noll
University of New Mexico
Albuquerque, New Mexico U.S.A.

W. Schulze
University of Southern California
Los Angeles, California U.S.A.

ABSTRACT

The National Energy Plan (NEP) sets as a goal the use of solar energy in two and a half million homes in 1985. A key provision of the NEP (as well as congressional alternatives) provides for the subsidization of solar equipment. The extent to which these subsidies (income tax credits) might offset the impact of continued energy price control is examined.

Regional prices and availability of conventional energy sources (oil, gas, and electricity) were compiled to obtain a current and consistent set of energy prices by state and energy type. These prices are converted into equivalent terms (\$/10⁶ Btu) which account for combustion and heat generation efficiencies. Projections of conventional fuel price increases (or decreases) are made under both the NEP scenario and a projected scenario where all wellhead price controls are removed on natural gas and crude oil production.

The economic feasibility (life cycle cost basis) of solar energy for residential space heating and domestic hot water is examined on a state-by-state basis. Solar system costs are developed for each state by fraction of Btu heating load provided. The total number of homes, projected energy savings, and sensitivity to heating loads, alternative energy costs and prices are included in the analysis.

⁴This work was supported by the Los Alamos Scientific Laboratory as part of their Regional Energy Assessment Program under contract to the U.S. Department of Energy.

[§]The general methodology for this study can be found in a technical completion report entitled, "Solar Energy: Policy and Prospects," prepared by the same authors for NSF - RANN in July 1976 and in a study entitled, "The Economics of Solar Home Heating," prepared for the Joint Economic Committee of Congress in March 1977.

I. INTRODUCTION AND SUMMARY

The National Energy Plan (NEP) proposed in April 1977 sets as a goal the use of solar energy in two and a half million homes by 1985. This report examines the potential for solar applications for both residential space and domestic hot water heating in single-family residences. Alternative energy prices for natural gas, heating oil, and electricity were projected for the period 1977 to 1985, using the proposed regulatory structure of the NEP (Section II). The costs of providing solar energy[†] as compared with these conventional fuels were then evaluated employing life cycle costing criteria (Section III). Economic feasibility[§] was examined on a state-by-state basis between 1977 and 1985, with varying time horizons for the life cycle comparisons. The analysis incorporated the two sets of proposed solar incentives--the NEP income tax credit structure and the House version--as well as a "no-incentive" case. States were identified where solar was shown to be less expensive than conventional fuels on a delivered $\$/10^6$ Btu basis.

Section IV takes a state-by-state projection of new housing construction through 1985 and examines the potential of solar residential space heating given projected trends on the availability of oil, gas, and electricity. A similar analysis is also made for domestic hot water. Included in the analysis is the total number of potential installations and associated energy savings for all three cases (NEP, House, and no-incentive structures). The associated costs to the government were computed for revenues lost through solar income tax credits.

The current system of subsidies for traditional energy sources (e.g., depletion allowances, combined with existing price controls) has a number of outcomes which economists consider highly undesirable. These include: 1) reliance on cheap energy from old sources such as natural gas, which tends to discourage the introduction of new technologies that are inherently more expensive, 2) distribution of fuel supplies to different regions of the country is distorted, and 3) discovery of domestic fuel sources may be discouraged by price controls. All of these factors are important to the future of solar energy.

[†] A more detailed description of both solar system performance criteria and costs is presented as part of Appendix A.

[§] Detailed formulation of the economic feasibility criterion employed in this study is presented as Appendix B.

The NEP does propose to continue some price controls. However, higher energy price ceilings would be allowed. This, in turn, would help the economic feasibility of solar energy. Under the proposed NEP, distribution of fuels between regions would also be changed because fuels like natural gas eventually would be sold at the same wellhead price to all consumers. This would tend to reduce regional biases against solar energy on the basis of regional availability of traditional fuels.

The third point mentioned above is especially important. If future domestic discovery of oil and natural gas is unlikely (assuming that our reserves are truly facing rapid depletion), then higher energy prices will not help in augmenting domestic energy supplies but will increase the relative importance of solar energy and other alternative energy sources.

The NEP (April 1977) does propose that initially in 1977 a 40% subsidy through an income tax credit be given for the first \$1000 spent for solar equipment, a 25% subsidy for the next \$6400 spent, and no incentive beyond a total system cost of \$7400. Thus, the maximum subsidy would be \$2000 towards systems that cost \$7400 or more. The incentives are then removed in steps through 1985, when they are phased out entirely.

The US House of Representatives (House) amended version of the NEP proposes a different incentive structure for solar systems. According to this structure, a 30% subsidy would be given to the first \$1500 spent for solar equipment, a 20% subsidy for the next \$8500 spent, and no incentive beyond a total system cost of \$10 000. The maximum tax credit would be \$2150. The incentives would remain unchanged until 1985, when they are eliminated.

Both of these incentive programs are aimed at solar water and space heating--the two technologies considered in this study.

The following points serve to summarize the basic findings from our analysis. Our results are, however, based on economic feasibility, a necessary, but not sufficient, condition for large-scale market penetration. The major conclusions are:

- The potential use of solar in residential space heating and domestic hot water applications is measurably enhanced by the proposed incentives.
- Solar domestic hot water heating appears far more promising in the near term than does solar residential space heating.
- Solar residential space heating costs remain higher than conventional natural gas and heating oil prices in both the 20- and 30-year life cycle cost time horizons, even with the inclusion of incentive structures.

- The application of solar energy for residential space heating purposes is competitive with the electric resistance alternative.
- If the 30-year life cycle cost criteria are employed, solar residential space heating does appear economically feasible for all states except those in the Northwest, Southeast, and South Central regions of the country.
- The 10-year life cycle cost criteria for solar domestic hot water application precludes economic feasibility compared with the natural gas and heating oil alternatives. However, movement to a 20-year system does allow solar energy to compete in some states with the natural gas and heating oil alternatives.
- Solar domestic hot water heating appears very promising when electric resistance is the alternative. With a 20-year system and either incentive structure, it is economically feasible in every state except Washington.
- Although the House version of the proposed incentives offers higher total credits, the NEP version is more effective because of the higher dollar credit in the range of most solar system costs (optimal solar fraction).
- The cost to the Federal Government (through income tax credits) per barrel of oil equivalent saved would be in the range of one-half to three-quarters the price of foreign supplies.
- There is little difference in the results when proposed NEP regulation of conventional fuels with proposed incentives is contrasted against deregulation without proposed incentives. The number of states and potential home installations with associated energy savings varies little between the two.

A summary of the principal results can be best made with reference to Map 1. This map presents the regions of the United States by state where solar domestic hot water heating would have the greatest impact under the National Energy Plan, with and without the proposed House version incentives for solar energy. The incentives clearly will have a dramatic impact since without them only eight states will be perceived as feasible by consumers through 1985. Alternatively, the addition of the incentives would result in the feasibility of all of the southern tier of states, the eastern seaboard, and some north central states. To obtain these results, we assume that consumers compare payments on a 10-year solar domestic hot water system to the savings in the cost of heating water with electricity. With more than 50% of new homes installing electric water heaters, the finding that solar energy is most competitive in this application implies that the solar incentives will have a dramatic impact.

II. CONVENTIONAL ENERGY PRICES

The economic performance of a solar space- or water-heating system must be evaluated in relation to the conventional heating sources that would be used otherwise. The majority of residential homes in the United States currently employ one or a combination of the following three energy types: natural gas, heating oil, and electricity. Although some homes use butane, propane, and other types of bottled gas, the numbers involved are relatively small when compared with the total housing stock. Hence, they are omitted from the analysis.

Regional variations in the prices and availability of these conventional energy sources must be known to assess more accurately the national pattern of solar economic feasibility. Data from the United States Bureau of Labor Statistics (BLS), Federal Power Commission (FPC), Federal Energy Administration (FEA), American Gas Association (AGA), and numerous private utilities were compiled to obtain a current and consistent set of prices by state and energy type. These prices are shown in Table I. Regional differences are highlighted by Maps 2 and 3 for natural gas and electricity, respectively. Since heating oil prices vary little by state, the only differences that would be discernible from a map display are in Texas, Oklahoma, Louisiana, and Arkansas.

Given this set of 1977 energy prices by state, a transformation is necessary to convert these prices into equivalent terms. Since the conventional common denominator is million Btu, the prices are stated as $\$/10^6$ Btu. Furthermore, these equivalent prices are converted to account for combustion and heat generation efficiencies. Finally, projected price increases (or decreases) of heating oil, natural gas, and electricity allow analysis of solar energy feasibility through 1985.

The descriptions below give an indication of the April 1977 National Energy Plan's (NEP) influence on the price of these energy sources, as compared with a projected scenario where all wellhead price controls are removed on natural gas and crude oil production.

Heating Oil

Domestic crude petroleum production is priced according to a two-tier system that imposes a ceiling of approximately \$5.25/bbl for old oil and \$11.28/bbl for new oil. Under the NEP, newly discovered oil would be allowed to rise over three years to the current 1977 world oil price of approximately \$13.50/bbl, adjusted

for domestic inflation thereafter. Where production from a marginal well is shown to be uneconomic at the \$5.25/bbl ceiling, that well would be eligible for the \$11.28/bbl price ceiling. At present, the average refiner acquisition cost of all domestic crude petroleum is about \$9.50/bbl. With 50% of domestic demand being met by OPEC imports, the weighted price between domestic and foreign oil is figured to be about \$11.75/bbl. Under the April 1977 proposed National Energy Plan, the two-tier pricing system would continue, so that the domestic weighted average price would slowly approach the world price as contracts expired and were renegotiated. In addition, one might expect the domestic portion of total supply to decline in the face of increased OPEC imports, which would also lead to real price increases in crude petroleum and heating oil.

In a decontrolled situation, one might expect the domestic weighted price of oil to increase rapidly to the world market price. Figure 1 shows the projected wellhead prices of crude petroleum resulting from both the NEP and decontrol. Under the oil pricing policy set forth in the NEP, the average refiner acquisition cost of domestic crude would approach the OPEC world price as new domestic sources come into production. When adjusted for imports, the total weighted acquisition cost is higher, reflecting the mix of higher priced foreign sources of crude petroleum. Under a policy of wellhead price decontrol, Fig. 1 shows the limiting case where all domestic contracts are immediately renegotiated to the world price. Although such immediate adjustment would not be likely, the rate of contract renegotiations might be high enough to push the domestic weighted average wellhead price to OPEC levels within a few years.

To arrive at residential delivered costs of heating oil, adjustment factors are added to the projected wellhead prices to account for refinery, storage, and distribution costs. Actual heating costs include the conversion to equivalent 10^6 Btu terms and correction for combustion efficiency.

Natural Gas

Natural gas flowing through interstate pipelines has been subject to FPC regulation since 1961 in order to protect ultimate consumers for unjust or inappropriate price increases implemented by gas producers. Since that time, the FPC has handed down several decisions that allow producers to charge higher maximum allowable wellhead contract prices for gas flowing from "newer" wells. In effect, the vintaging system now in force allows for a three-tier pricing system,

the particular prices being dependent upon the date at which gas was brought into production from a specific well.

The original NEP prepared by the Executive Office of the President proposes a new commodity value pricing approach that applies to all new gas wherever it is used. Under this proposal, all new gas sold anywhere in the country from new reservoirs would be subject to a price limitation at the Btu equivalent of the average refiner acquisition price (without tax) of all domestic crude oil. That price would be approximately \$1.75/mcf (\$10.15/bbl) at the beginning of 1978, and would approach \$2.32/mcf (\$13.50/bbl), the average world price of oil in 1977 dollars. New gas entitled to this incentive price would be limited to truly new discoveries.

In essence, the NEP establishes a fourth tier in the natural gas pricing system, but allows for the eventual possibility of a two-tier system if all pre-January 1978 contracts are renegotiated at the maximum allowable ceiling of \$1.42/mcf plus inflation. Furthermore, "new" intrastate gas contracts will be limited to a maximum wellhead ceiling of \$1.75/mcf (allowed to increase in accordance with the average refiner acquisition cost of domestic oil), which, in most cases, has the effect of bringing higher intrastate prices into line with lower interstate prices, thus eliminating the current distortion in relative supplies dedicated to the two markets.

What implications does the NEP have concerning projected wellhead prices? The plan guarantees natural gas price certainty, but it doesn't give an indication of how the relative quantities of the four vintaged gases will change over time. As older contracts expire or are renegotiated, progressively larger volumes of interstate gas will be priced at the higher ceiling of \$1.42/mcf. In addition, the relative percentage of \$1.75/mcf (or higher) gas will increase as truly new discoveries are brought into production. The combined effect under the NEP will be for the national weighted average wellhead price (currently equal to \$0.56/mcf) to asymptotically approach the ceiling set by the Btu equivalent of the average refiner acquisition cost. The rapidity of this movement, of course, depends upon the rate and level of recontract pricing, current contract expiration, and new gas production.

Under a scenario of wellhead price decontrol, one might expect a more rapid rate of recontracting, which would bring the price of previously controlled interstate gas contracts into line with new or existing decontrolled intrastate contract prices. Furthermore, the wellhead price would increase at an annual rate,

at least to a level set by OPEC (world price of oil) at \$13.50/bbl, which is equivalent to approximately \$2.32/mcf.

Thus, we project average wellhead gas prices to be \$1.56/mcf (1977 dollars) by 1985 under the NEP, or alternatively, \$2.32/mcf with total deregulation. Figure 2 shows the projected behavior of natural gas wellhead prices under these two alternatives. Note that with decontrol in 1977, we assume a discreet jump in weighted wellhead prices due to immediate recontracting, with annual increases up to the OPEC world price equivalent. Adding a residential adjustment factor to each year's wellhead price and correcting for combustion efficiency results in the delivered cost to the consumer in $\$/10^6$ Btu on a state-by-state basis.

Electricity

Segments of the NEP introduce measures to shift electric utilities away from the use of natural gas and fuel oil boilers to a more widespread use of coal and alternative energy sources. This would free substantial quantities of the liquid hydrocarbons for higher use or less substitutable energy end uses such as residential home heating. According to projection analysis by the NEP staff, real electricity prices in 1985 would increase in certain regions, decrease in other regions, and remain unchanged elsewhere. In our study, we assumed no annual increase in the real price of electricity through 1985.[†]

Under decontrol, the price of liquid hydrocarbons likely would increase quite rapidly, thereby affecting utility costs. These increased costs would be passed on to consumers in the form of monthly purchase of energy adjustment clauses or increased rates. In this case, we assume that a 2% real rate of electricity price increase would prevail through 1985 and beyond. From these alternative sets of electricity prices, residential delivered costs are derived for both electric resistance heating and electric heat pumps.[§]

[†] An underestimate of electricity prices in select areas may belie the number of states where economic feasibility could be shown. However, sensitivity analyses of the results indicate that this may be a real problem only in a few states.

[§] The difference between these two modes of electrical space heating lies in the heat generation efficiencies otherwise known as Coefficients of Performance (COP). We assume electric resistance to have a COP of 1.0, while the COP for heat pumps varies by state, but falls in the range 1.25 to 2.25.

Life Cycle Versus Current Costs

When considering an investment in solar energy equipment, a homeowner may or may not have a specific set of expectations regarding the future costs of conventional energy sources that would otherwise be used to heat the living space or domestic hot water. If no real price increases were expected, the homeowner could only react to current prices when evaluating an investment in a solar energy system. However, if a homeowner did expect energy prices to increase, he could compare the additional mortgage cost of the solar system to an average of the series of expected increasing prices.[†] This average or equivalent annual life cycle energy price would be higher than the current cost counterpart and would encourage the homeowner to make a more proper economic decision with regard to a solar system investment. Thus, our analysis assumes that the homeowner expects further increases in most energy costs. We use a set of delivered energy prices based upon annual equivalent life cycle costs stated in 1977 constant dollars.

Figures 3 and 4 show the projected average delivered costs of energy to users in New Mexico and Wisconsin through 1985 under the April 1977 NEP. These prices are stated in constant 1977 dollars. The annual prices of natural gas and heating oil will be higher than those depicted in Figs. 3 and 4, since their real prices increase over time. However, electric resistance and heat pump prices remain constant under both current and annualized costing modes, since no real price increases are assumed for electricity under the NEP.

III. ECONOMIC FEASIBILITY

This section examines the economic feasibility of solar energy for residential space heating and domestic hot water on a state-by-state basis. For the purposes of this study, solar energy is feasible when its cost in $\$/10^6$ Btu is equal to or less than the cost of providing the same quantity of an alternative energy source. The prices of the alternative energy sources are described in the previous section. Performance analysis of solar systems is based upon previous

[†]For a formal treatment of the methodology employed and derivation of these equivalent annual life cycle energy costs, see Appendix B.

work performed at the Los Alamos Scientific Laboratory.[†] From that work, one representative city was selected for each state, as shown in Map 4, along with the associated heating degree days (DD). Solar system costs were developed for each state in 5% intervals of the fraction of Btu heating load provided, ranging from 20% to 90% for residential space heating systems and from 10% to 95% for domestic hot water systems. Representative solar system costs by state are listed in Tables II and III for residential space heating and domestic hot water, respectively. Maps 5 and 6 portray solar systems cost in a comparative manner. Ranges of costs for all states are shown with a 50% solar fraction for residential space heating and 85% solar fraction for domestic hot water. These fractions do not represent the most cost effective or optimal sizing for most states, but serve rather as a convenient point of comparison.

The economic feasibility analysis uses prices and costs projected to 1985 in 1977 dollars, and assumes a 10- to 20-year life for domestic solar hot water systems and a 20- to 30-year life for residential solar space heating systems. Alternative energy prices in 1977 dollars were discussed in the previous section. Solar system costs as represented in Tables II and III are assumed to remain constant in 1977 dollars, i.e., no real price increase or decrease in installed system prices. Space heating loads for a new home constructed between 1977 and 1985 will vary by state depending upon the average number of heating degree-days (DD), as shown on Map 4. For example, a home of 1500 ft² with a heating "load" of 10 Btu/DD/ft² would have a total yearly space heating load of $65 \cdot 10^6$ Btu in Albuquerque, New Mexico, and $110 \cdot 10^6$ Btu in Madison, Wisconsin. Domestic hot water heating loads will vary by state depending upon the temperature differential of the water before and after heating. The differential here is assumed to be a constant 60°F for all states throughout the year, and correcting for load profile (time of day needs) results in a $20 \cdot 10^6$ Btu yearly requirement.[§]

[†] For a fuller discussion on the performance and cost of solar heating systems used in this study, see Appendix A.

[§] It is recognized that this load may somewhat overstate the load in southern climates and understate loads in northern climates. State differentials will be used as they become available. The use of a $20 \cdot 10^6$ Btu heating load here should not affect final results and implications significantly.

Residential space heating systems can be either air or liquid. The liquid systems will generally have higher costs associated with the collector area and lower collector-independent costs than a comparable air system.⁺ This results in lower total costs for those liquid systems providing small solar fractions. However, once a threshold solar fraction is reached, liquid systems become more expensive. In the analysis reported here, that threshold level is between 40% and 60% solar, which is also the range of optimal solar fraction for most states. Thus, our use of only air systems for the residential space heating feasibility analysis has no appreciable effect upon study results and implications.

The costs of solar energy systems (both with and without proposed incentives) are contrasted against the principal energy forms used for residential space heating and domestic hot water: gas, oil, and electricity--both resistance and heat pumps. Propane, butane, and other liquified gases are used in only a small percentage of homes in the United States. In addition, on a Btu equivalent basis, the price of these fuel types is not appreciably greater than heating oil. Therefore, these fuels are excluded from this analysis.

In the following discussion of actual results, several different time horizons are included in the life cycle computations of alternative energy prices and solar system costs. For domestic hot water comparisons, both a 10- and 20-year life are assumed. The 10-year figure is close to conventional warranties on domestic hot water systems, as well as the traditional loan life for this type of home improvement. The 20-year figure represents the assumed life expectancy of domestic solar hot water systems used in many other comparative analyses. In addition, liquid systems have been given an expected life of not more than 20 years by many investigators examining solar technologies for residential applications. For residential space heating comparisons, both a 20- and 30-year life are assumed. Liquid systems employed for space heating purposes will likely be limited to the 20-year figure. In addition, most studies in the past have placed the expected lifetimes of residential solar space heating systems around 20

⁺Collector independent costs for air systems were almost twice those associated with liquid systems. On the other hand, collector dependent costs for liquid systems are \$2-3 more per ft² of collector.

years. There are, however, arguments developing to place the expected lifetimes closer to the 30-year figure: two of these being that the mortgage length for new home loans and present guarantees for newly installed air systems by several solar firms are 30 years. For both solar system applications, a longer assumed solar life results in a lower solar cost to the consumer per year in terms of $\$/10^6$ Btu, thus making solar systems more competitive.

Solar system costs will be subjected to two sets of incentives: one being the initial proposal from the April 1977 National Energy Plan, which will generally be referred to as the NEP incentive structure in the following discussion; the other being the September 1977 House of Representatives Bill 8444, which will be referred to as the House incentive structure. Nominal dollar values for both sets of proposed incentives for a representative solar system, both residential space heating and domestic hot water, are given in Table IV. Briefly, the NEP incentive structure allows a 40% income tax credit (incentive/subsidy) to the first \$1000 spent for solar equipment, a 25% income tax credit for the next \$6400 spent, and a maximum credit of \$2000 towards systems that cost \$7400 or more. The incentives (income tax credits) are then removed in steps, phasing out entirely by 1985. The House incentive structure allows a 30% income tax credit to the first \$1500 spent for solar equipment, a 20% credit for the next \$8500 spent, and no incentive beyond a total system cost of \$10 000. Maximum credit towards an individual's income tax liability would be \$2150, with this set of proposed incentives continuing without reductions until 1985, when they are to be eliminated.

As an example of the impact of the proposed incentives on solar costs in 1977, consider Albuquerque, New Mexico. In this city, based upon our performance analysis and cost assumptions, provision for 50% of a new 1500 square foot home's space heating demand would require 236 ft^2 of low-performance collector with a total installed price of \$5436. The House version of the solar incentives would reduce this cost by \$1136, or about 21%. Comparable numbers for the NEP version would be \$1509 and 28%, respectively. To provide domestic solar hot water for the same house using a low performance collector, but with 85% of the load taken by solar, 65 ft^2 of collector would be needed with an entire system installation cost of \$1314. The House incentives in this case would be \$394 for a 30% cost reduction to the consumer, as compared to \$479 and 36% with the NEP incentives. If we use Madison, Wisconsin, as our sample community, costs are \$9,432 for a 532 ft^2 space heating system and \$1941 for a 108 ft^2 hot water

system providing 50% and 85% of the load, respectively. Similar calculations give a House incentive of \$2036 (22%) and \$532 (27%), respectively, for space and hot water systems. The NEP incentives would be \$2000 (21%) and \$538 (28%) for space and hot water heating, respectively. In general, the NEP (April 1977) proposed incentives would result in somewhat higher tax credits for domestic hot water solar applications, and, for many of the states in space heating applications, somewhat lower tax credits due to the reduction in the rate of income tax credits.

We turn now to a brief discussion of the solar feasibility results.

Residential Space Heating

The costs of solar residential space heating systems with either incentive structure or either assumed life cycle cost parameter (20 or 30 years) remain economically unfeasible compared with both natural gas and heating oil prices. Stated another way, even with the proposed incentive structures and the longer 30-year life, the costs of providing energy from a solar system is higher on a Btu equivalent basis than either conventional natural gas or heating oil systems.

However, if electric resistance is the alternative energy form, solar economic feasibility may be achieved in a number of states by 1985 using either the NEP or the House incentives, and either the 20- or 30-year life cycle cost comparisons. Those states are displayed in Maps 7 and 8 for the 20- and 30-year life systems, respectively. In these specific states, the cost of electricity per kWh, the total heating load, and the incentives all combine to work for economic feasibility.

When examining the feasibility of solar energy compared with electric resistance, the first comparison is under the 20-year life cycle costing assumptions, as shown in Map 7. Economic feasibility is achieved by six states in the Midwest and New England with energy prices remaining controlled and with no incentives. With the House incentives, an additional 9 states, for a total of 15, portray feasibility. The NEP incentive structure is even more effective, with another 5 states (for a total of 20) reaching parity.

When the economic life of solar residential heating systems is increased from 20 years to 30 years, the annualized costs of solar energy drop sufficiently for additional states to display economic feasibility over electric resistance heating. Map 8 shows that an additional 9 states (for a total of 15) demonstrate

economic feasibility using no incentives under the 30-year life cycle cost comparison. This increases by another 16 states (for a total of 31) when the House incentives are used; and further increases by 3 states (for a total of 34) under the NEP incentives. These additional states are generally located in the Southwest, upper Rocky Mountain, and North Central regions. In many of the remaining states where feasibility cannot be shown, the incentives are not quite strong enough to force economic parity.

In summary, both the NEP incentives and the 30-year life cycle costing enhance the economic feasibility of solar heating over electric resistance heating.

When heat pumps are employed (Maps 9 and 10), the \$/Btu cost of electricity drops enough that only in a few northern states is economic competitiveness achieved with either set of incentives or life cycle cost parameters.

Against the deregulated set of alternative energy prices described in the previous section, solar energy costs without the proposed incentives still remain above the now higher natural gas and heating oil prices. Thus, deregulation of natural gas and heating oil prices does not appear to enhance solar feasibility. However, electricity price increases under a deregulation scenario do result in a greater number of states achieving solar economic parity with resistance heating for both 20- and 30-year life cycle cost comparisons when contrasted with regulated energy prices with or without proposed incentives. These results are displayed in Maps 11 and 12 (20-year and 30-year life cycle cost assumptions, respectively). Employment of heat pumps reduces the \$/Btu cost of an equivalent quantity of energy provided by electricity to levels below solar economic parity in most states, with now only five Midwest and New England states showing solar competitiveness by 1985.

Domestic Hot Water

Solar applications for domestic hot water appear more promising based upon the feasibility analysis. Economic feasibility is achieved for a number of states when solar is contrasted against all three alternatives: natural gas, heating oil, and electricity. Only electric resistance is considered since heat pumps would not be employed solely for heating domestic hot water. Even though natural gas and heating oil prices remain at levels not significantly different from those of today (1977 dollars), the proposed incentive structures lower the cost of solar systems sufficiently to achieve economic feasibility in a number of

states when a 20-year life cycle cost comparison is used (see Maps 13 and 14). However, economic feasibility is precluded under the 10-year life cycle cost analysis, since the solar cost is now higher on a $\$/10^6$ Btu basis than the natural gas and heating oil prices.

Solar energy does exceptionally well compared with an electric resistance domestic hot water system. Under 20-year life cycle cost analysis, economic parity is a reality today in all but one state. The exception is Washington, where there is inexpensive hydroelectric power in combination with a cloudy site. The fraction of the domestic hot water load supplied by solar energy is between 70% and 90% in all states except Oregon (65%). When 10-year life costing governs the analysis, the number of states is reduced significantly under either incentive structure. Domestic solar hot water systems fall from parity in much of the Northwest, upper Rocky Mountain, Central Plains, and North Central regions. These results are portrayed in Maps 15 and 16 for the 10- and 20-year life cycle cost assumptions, respectively.

Clearly, the pattern discussed earlier in comparing solar and electric space heating is being repeated for hot water heating. The incentives increase the feasibility of solar energy, with the NEP set being most effective. Likewise, the longer life cycle cost parameter (20- versus 10-year life) increases its feasibility. Under the 20-year lifetime, both incentive structures give rise to an additional 13 states compared with the "no incentives" computations. Under the 10-year time horizon, the difference is 18 and 26 states for the House and NEP incentive structures, respectively. For both the 10- and 20-year lifetimes, the pattern is generally the same when incentives are considered: movements are northerly from the high solar insolation regions and outward from the high alternative energy price areas.

If collector independent costs are doubled for solar domestic hot water systems and collector dependent costs are raised a couple of dollars per ft^2 of installed area from those assumed above, total system costs for a given solar fraction (say 85%) are increased between 35% and 45% in almost every state. When the economic feasibility analysis employs these higher total systems costs with either set of proposed incentives, very little difference is found in the total number of states achieving economic parity against the natural gas, heating oil, and electric resistance alternatives. Thus, with solar domestic hot water installations being priced measurably higher than portrayed in Table III and Map 6,

and assuming a 20-year lifetime, economic feasibility is still demonstrated for most of the country as compared with electric resistance, for the southern and eastern seaboard states as compared with natural gas, and for the western and upper eastern seaboard states as compared with heating oil.

Even with the higher natural gas and heating oil prices resulting from deregulation, solar energy costs using either set of the proposed incentives remain above these alternative prices in all but a few states (Southwest and Northeast). However, electricity price increases again result in solar economic feasibility today in all but the State of Washington under 20-year life cycle costing. The 10-year life cycle cost analysis drops the number of states displaying economic feasibility compared with electric resistance to 28. This is not significantly different from the results of using the incentives (Map 15). The fraction of hot water heating load supplied by solar energy is between 60% and 90% in all states.

Sensitivity Analysis

Solar feasibility by state, year, and fraction is sensitive to the specific parameters used in the analysis. Residential solar space heating doesn't compete with natural gas or heating oil under either the proposed incentive structures or a deregulation scenario. The feasibility of solar space heating compared with electric resistance heating is considerably increased when the system life is extended from 20 to 30 years. The annual payment necessary to finance a 30-year system is 25% lower than the payment associated with a 20-year loan. This 25% margin is substantial enough to make solar space heating feasible in the East, North Central, Northern Rocky Mountain, and Southwest regions, although feasibility with a 20-year system life was not attained in these areas. For comparison, consult Map 8 for a 30-year system life and Map 7 for a 20-year system life, both based upon NEP energy price patterns.

An opposite effect occurs if capital recovery factors⁺ are based upon a 4% real (inflation free) rate of interest versus the 2.5% rate used as the

⁺ Simply stated, a capital recovery factor allows one to transform a loan into yearly payments at a given interest rate and length of time such that at the end of the period the loan is completely paid off. The capital recovery factor tool is employed as part of our overall methodology in the economic feasibility analysis. For a more precise formulation, see Appendix B.

standard in this analysis. Thus, assuming 6% inflation, a 10% (4% real plus 6% inflation) nominal loan for 30 years gives an almost identical annual payment as an 8.5% (2.5% real plus 6% inflation) nominal loan for 20 years. This is due to the asymmetric influences exerted by system life on the one hand and loan finance rates on the other.

Other parameters varied in the analysis were the specific area-dependent and -independent costs of solar residential space heating systems. We allowed these costs to decline at a rate of 6% per year, which is the same as assuming that the solar tax credit incentives (both NEP and House) remained constant in real 1977 terms through 1985, given a 6% annual rate of inflation. In Senate Bill 1472, a bill to implement the taxation aspects of the National Energy Plan of April 1977, the incentives are stated as allowable tax credits on fractions of solar systems cost to a maximum of \$2000. These fractional increments decline in a stepwise manner through 1984, at which point they are entirely eliminated. If inflation continues at a 6% annual rate, then the incremental fractions actually decline at a rate faster than that stated in the bill. For the incentives to remain constant between 1977 and 1985, one of two things must happen: 1) the annual rate of inflation must equal zero per cent with no real decrease in solar system prices, or 2) the annual real rate of decrease in solar system costs in general equals the annual rate of inflation. Most people in the solar industry do not foresee real cost declines on the order of 6% per year. However, recent experience might support the expectation of a continued 6% annual rate of inflation. A similar reason supports the conversion of proposed income tax credits in the newer House version of solar incentives to real terms in our preceding analysis.

Even when these real cost decreases in solar systems were taken into account, solar space heating systems were still not competitive against natural gas or heating oil alternatives under the NEP price structure or with deregulation. Against electric resistance and heat pumps, only a marginal effect was obtained. This outcome is due to the fact that electricity prices under the NEP are projected to remain relatively constant in real terms and the incentives are at their maximum real value in 1977. Hence, if feasibility does not occur in 1977, it would not be expected to occur at any future point in time unless large drops in real solar costs are expected.

However, under the deregulation scenario, the feasibility pattern is again extended against the electrical heating alternatives. The 2% electricity price increase makes solar residential space heating more attractive and, in fact, feasible for additional eastern seaboard and north central states in the late 1970's and early 1980's.

Significant changes in prices would be necessary for solar systems to compete with each of the four energy alternatives (natural gas, heating oil, electric resistance, and electric heat pump) under the proposed NEP. Table V shows the minimum point of the solar average cost curves when the NEP incentives (similar numbers would apply when the House incentive structure is used) are at a maximum for two representative cities: Albuquerque, New Mexico, and Madison, Wisconsin. All prices are stated in $\$/10^6$ Btu for 1977, with the price of conventional alternatives stated in annualized terms (life cycle equivalents), and the real price of solar given at its minimum value, which corresponds to the maximum real incentive offered under the NEP structure. In both cities, solar energy is currently competitive against electric resistance heating, although natural gas and heating oil are far cheaper alternatives. For solar energy to compete in the northern states against natural gas space heating, the cost of solar systems would have to decrease significantly or the price of natural gas would have to increase by 50% to 150% depending upon the particular state. In the southern states, these decreases (or increases) must be up to 400% in order to obtain economic feasibility for solar energy. To compete against heating oil, solar prices would have to drop approximately 75% to 100% throughout most of the United States. These percentages would be much smaller if the same systems can be expected to last for 30 years rather than 20 years.

IV. HOME AND ENERGY IMPACTS

The potential total number of homes and energy savings were based primarily upon new single-family construction between 1977 and 1985 at an average of 1.3 million units per year, using the assumptions made in a previous study.[†] The allocation of this number to each state was based upon two principal components: 1) the present stock of single-family homes, and 2) the projected number of new

[†]"The Economics of Solar Home Heating," prepared for the Joint Economic Committee of Congress, March 1977, by the same authors.

household formations. The present stock of single-family homes influences replacement decisions, while new household formations place demands for net housing starts and vacancy additions. Thus, gross housing starts (single-family residences) will equal the sum of net additions, inventory replacements, and units constructed but remaining vacant.

The type of fuel to be used in the new housing construction for both residential space heating and domestic hot water was based upon practices established during the 1970 to 1975 timeframe. During this period, there was a move away from natural gas and heating oil to electricity in most of the country; from butane, propane, and similar fuels in the rural areas. This results in a per cent composition by fuel type for each state measurably different from that evidenced by the total housing stock in either 1970 or 1975. Using either the 1970 or 1975 total housing stock, fuel composition percentages drastically would distort likely patterns of usage between now and 1985. Use of new housing (housing constructed between 1970 and 1975) construction fuel type installations presents a much more realistic picture of likely patterns. A major assumption of continuation of the 1970 to 1975 fuel consumption patterns was that natural gas curtailments, new hookup moratoriums, and heating oil shortages will not increase (relatively) before 1985. Increased use of electricity is a certainty to the extent that natural gas (principally) and heating oil is not available, whether because of price controls or other reasons.

Several maps have been constructed to demonstrate some of the interactions between projected new housing starts and fuel type installations, and also to give some indication of the potential impacts from solar installations. Maps 17, 18, and 19 display projected total new single-family homes between 1977 and 1985 for residential space heating installations by fuel type: natural gas, heating oil, and electricity, respectively. The blank states indicate that less than 1000 installations are projected. Natural gas installations lead the way, followed fairly closely by electricity, with heating oil a distant third in most states except the traditional New England and Eastern Seaboard regions. Thus, likely solar installations are implied by contrasting these maps with the maps portraying economic feasibility for residential solar space heating applications.

Maps 20, 21, and 22 display projected total new single-family houses between 1977 and 1985 by fuel type for domestic hot water installations. Here natural

gas and electricity are likely to be far more prevalent than heating oil, excepting only two or three states. Heating oil is not used for hot water heating as extensively as for space heating. The trend indicates that this divergence will continue even in those states where heating oil has traditionally been the principal fuel for all heating purposes. States will have few heating oil installations for hot water purposes (see Map 21). The states that are projected to have less than 1000 installations are left blank. Map 20 shows that natural gas installations may be zero or near zero in the Northwest and New England regions.

The number of potential homes was based upon summing the new single-family construction (as shown in Maps 17 through 22) for those states displaying economic feasibility for both incentive structures and fuel type comparison by year to 1985. This total computed figure was reduced by 50%. It was assumed that only one-half of all potential new homes where economic feasibility is achieved will be capable of accommodating solar energy systems because of orientation (primarily), structure, and institutional constraints. This is likely to be much truer for residential space heating than domestic hot water applications. However, for purposes of these preliminary calculations, the 50% fit appears reasonable. This assumption will be modified as more information is developed.

The estimates presented here should not be interpreted as market penetration projections. Given that economic feasibility is a necessary but not sufficient condition for marketability estimates, our projections serve as an expected upper bound on consumer purchases and installations.

Energy savings were based upon specific fuel comparisons. The total energy load for space heating is the quotient of heating degree-days and assumed heat load of $15 \cdot 10^3$ Btu/DD per home. The total energy load for domestic hot water heating is $20 \cdot 10^3$ Btu per household. For any given fuel type, the fraction of the total energy load provided by solar energy for each home within a specific state was taken from the economic feasibility results (only the states were shown in the previous section). This fraction (specified as Btu) was multiplied by new construction (under the 50% fit assumption) where that given fuel type is used as a backup. This results in the potential energy savings attributable to solar by year for each state.

Two measures of potential energy savings are employed in the following discussion. One is the total quantity of Btu, which makes interfuel comparisons

easier. The other, and possibly more meaningful measure, is of energy equivalency, that is, the Btu are converted into conventional units by fuel type and subsequently converted to a common "barrels of oil" (bbl) measure for presentation here.

In addition, two different concepts of potential energy savings are presented. The first is the accrued or accumulated savings from 1977 to 1985, the timeframe of both this analysis and the proposed National Energy Plan. This number represents the savings to be realized from solar installations between the time of their installation until 1985. The second concept is a little more comprehensive: it represents a total energy savings that might be expected over the life of a solar installation. This is calculated by multiplying the energy savings attributable to each solar installation (whether residential space heating or domestic hot water) put in place between 1977 and 1985 by the assumed life of solar installation for this analysis, either 10, 20, or 30 years.

The cost to the government in the form of income tax credits accrued over the 1977 to 1985 timeframe is also calculated. The dollar subsidies (income tax credits) for each potential solar installation are totaled to arrive at the "total cost to government" figure.

The home and energy savings implications are summarized in Tables VI, VII, VIII, and IX. The first two tables, VI and VII, were constructed for solar residential space heating installations based upon 20- and 30-year life cycle cost analysis, respectively. Tables VIII and IX are similarly based upon 10- and 20-year life cycle cost analysis, respectively, of solar domestic hot water installations. Each table contains the results⁺ considering both the NEP and House incentives and the "no incentives" case. The number of homes is again 50% of projected new single-family houses proportioned by fuel type for heating purposes.

For residential space heating, as was demonstrated in the previous section, solar systems are likely to supplant only electricity between now and 1985 under both the 20- and 30-year life cycle cost criteria. Both natural gas and heating

⁺The figures in parentheses within each table represent the accumulated savings between year of installation and 1985 for the number of solar systems portrayed in columns one to three.

oil remain priced sufficiently below solar such that economic feasibility is precluded. Economic feasibility against electricity applies almost exclusively to resistance heating (Maps 7 and 8) with heat pump parity surfacing only in a few northern states (Maps 9 and 10). If the 1970 to 1975 fuel composition patterns continue, approximately 255 thousand new homes may install solar space heating systems by 1985 to replace (supplement) the electric resistance alternative, assuming the 20-year life cycle cost comparison and House incentive structure. Total savings between 1977 and 1985 would be close to $60 \cdot 10^{12}$ Btu (0.06 quads) or approximately 12% of the electricity that would have been consumed by new homes using electric resistance heating without solar augmentation. Cost to the federal government through tax credits would be in the range of \$363 million (1977 to 1985 timeframe--1977 dollars). Total energy savings over the solar residential space heating system's life of 20 years would approach $219 \cdot 10^{12}$ Btu (0.22 quads) or 37 million barrels of oil. This might also be interpreted as 180 kWh (64 thousand GWh total) saved per dollar of government investment. Capacity reductions (reductions from what was expected without solar supplement) could potentially reach 50 MWe during the 1977 to 1985 timeframe.

More home installations and larger energy savings are generated by the NEP incentive structure than under the House version (Table VI). This is because under the NEP structure the actual dollar tax credit given was greater for most of the states. Approximately 325 thousand solar installations in homes with an energy savings of $72.7 \cdot 10^{12}$ Btu (12.5 million barrels of oil equivalent) might be expected by 1985 under the NEP incentive structure. This is 70 thousand more homes and over 2 million barrels of oil equivalent than under the House version. Government expenditures are expected to rise \$86 million to about \$450 million during the 1977-1985 timeframe. Although the number of states increases significantly when contrasting the NEP and House incentives, the number of potential installations and energy savings does not increase commensurately. Relatively speaking, the states added are not as populated.

As expected when one moves from a 20-year to a 30-year time horizon in the life cycle cost analysis, the number of potential installations and energy savings increases dramatically. Possibly more important is that the increment between the "without" and "with" incentive cases is far larger under a 30-year regime than for 20 years. Natural gas and heating oil alternatives are still

lower than the subsidized solar costs. However, the differential narrows considerably in many of the states. Table VII displays the results for the electric resistance alternative comparison. Under the NEP incentive structure, about 925 thousand solar installations in homes could be expected, with an energy savings of $711 \cdot 10^{12}$ Btu (122 million barrels of oil equivalent). Over the 30-year life of all installed systems with the solar fraction between 40% and 60%, the total Btu savings could approach a quad. Cost to the government in the form of income tax credits would be just over \$1.2 billion. As seen in Table VII, the total number of homes with potential energy savings is lower under the NEP incentive structure than the House regime, even though more states display economic parity. As the NEP incentives decrease, solar costs increase measurably. Thus, under the NEP structure some states reverse from economic feasibility to economic unfeasibility, and then revert back to economic parity the following year. Thus, the potential total number of home installations and corresponding energy savings resulting from the NEP incentives is somewhat less during the 1977 to 1985 time horizon than under the House incentive structure, where no incremental reduction takes place.

The additional states displaying economic parity under the 30-year life cycle cost analysis are located south and west of those under the 20-year time horizons. These additional states are in the Southwest, upper Rocky Mountain, and North Central regions. Also, the number of potential installations is proportionally greater than the commensurate energy savings. That is, when the time horizon increases from 20 years to 30 years, the percentage increase in installations is greater than the percentage increase in energy savings due to the generally lower heating loads supplied by each additional solar system.

Solar applications for domestic hot water heating appear much more promising than for residential space heating. Tables VIII and IX display the results of the economic feasibility analysis, translated to potential home installations and energy savings, under a 10-year and a 20-year time horizon, respectively. As shown previously in Section III, the natural gas and heating oil alternatives remain below solar costs under either the NEP or the House incentive structure, using a 10-year life cycle cost approach. Therefore, Table VIII contains numbers for only the electric resistance alternative. Going from a 10- to a 20-year life cycle does allow solar economic parity with both natural gas and heating oil in

a number of states, as well as significantly increasing the number of states when electric resistance is the alternative. Table IX contains this set of results.

The potential number of installations and associated energy savings are nearly doubled with the proposed incentives from that without the incentives under the 10-year time horizon. As with the residential space heating solar applications, the shorter timeframe (20 years) in the economic feasibility analysis gives rise to a situation where the initial NEP incentive structure performs slightly better than the newer House version. Under either structure, the total energy savings during the 1977 to 1985 timeframe is over $175 \cdot 10^{12}$ Btu, or the equivalent of 31 million barrels of oil. With a system life of 10 years, total energy savings may approach $320 \cdot 10^6$ Btu for all solar domestic hot water heaters installed. Barrels of oil equivalent could reach nearly 60 million, with the cost to the government close to \$640 million for those same solar installations. If the systems installed were to remain operable for 20 years (the timeframe many believe to be realistic for domestic hot water systems), the energy savings potentially attributable to said installed systems would be twice that contained in Table VIII (10-year savings). Costs to the government would not change, but the Btu per dollar invested would increase dramatically. Home-owners would also benefit significantly, receiving much more heat from the installed solar system than went into the life cycle costing computation.

Solar systems installed for domestic hot water in new construction fares much better than those for application in residential space heating, with the longer time horizon in the economic feasibility analysis (30 years for space heating and 20 years for water heating). Against natural gas (Table IX), solar systems in the southern and eastern seaboard states as well as the western and southwestern states achieve economic parity. By 1985, approximately 465 thousand new homes might be expected under the newer incentive structure with total energy savings accumulated to 1985 from all solar installations approaching $36 \cdot 10^{12}$ Btu (between .03 and .04 quads), or 36 billion cubic feet of natural gas. Energy savings attributable to those solar installations over their 20-year life might reach $123 \cdot 10^{12}$ Btu (close to a .13 quad) or 128 billion cubic feet of natural gas. Cost to the government in 1977 dollars would be approximately \$132 million, with an equivalent barrels of oil savings approaching 22 million. Reductions to capacity could reach 21 MMscf/day if coal gasification facilities were to supply the alternative gas.

In this situation, the NEP incentive structure performs much better in terms of potential homes and energy savings. Over 735 thousand installations potentially could be expected with $60 \cdot 10^{12}$ Btu saved between 1977 and 1985. Cost to the government would be slightly over \$210 million, with total energy savings over the solar installations' 20-year life approaching $187 \cdot 10^{12}$ Btu, or the equivalent of 32 million barrels of oil.

Although the number of states where solar achieves economic parity (20-year life cycle costing only) against heating oil is large under both incentive structures, the potential total number of new homes and energy savings is relatively small due to its (heating oil) lack of use for domestic hot water heating. Approximately 120 thousand homes with a Btu fuel savings of $10.5 \cdot 10^{12}$ Btu during the 1977-1985 time period might reasonably be expected if past trends continue (heating oil use for domestic hot water) and with the new incentive structure factored into the analysis. Total energy savings attributable to solar systems over their assumed 20-year life may approach $30 \cdot 10^{12}$ Btu (approximately .03 quad) or 5.2 million barrels of oil. Cost to the government would be approximately \$35 million, or represent an investment of \$7 per barrel of oil saved. Reduced production (whether from domestic wells, imports, or potentially a syn-fuels plant) could be around 10 thousand barrels per day.

The situation of moving from the House to the NEP incentive structure is reversed here (as opposed to the situation with the natural gas alternative). Because of the incremental reduction in the given percent of income tax credit and, thus, dollar amount, some of the states flip-flop between economic feasibility and non-feasibility from year to year. This, of course, leads to a reduction in the potential number of installations and energy savings from that under the newer House incentive structure.

Because economic feasibility for solar vis-à-vis electric resistance was shown in all states except one (Washington) under the 20-year life cycle cost criteria, over 3.9 million new homes could be capable of solar installations by 1985. [Under the 10-year life cycle cost criteria, the number of homes was only 2.2 million, discussed briefly above.] With that taking place, nearly $325 \cdot 10^{12}$ Btu or 93 thousand GWh could potentially be saved through 1985. Total energy savings that could be realized over the installations' given 20-year life would approach $1300 \cdot 10^{12}$ Btu (over 1.3 quads) or 378 thousand GWh. There is no difference in the number of states under either incentive structure; therefore, only

slight differences exist in total potential installations and energy savings. What differences there are can be attributable to the flip-flop of several states brought on by an incremental reduction in the percentage incentive under the NEP structure. Cost to the government during the period 1977 to 1985 would be between \$1.1 and \$1.2 billion (House and NEP structures, respectively). This transforms into 325 kWh saved per dollar invested. Potential reductions to needed generating capacity could surpass the 2000 MWe level.

It is interesting to note that the change in total states displaying economic parity is much greater under the 10-year criteria than under the 20-year life cycle cost analysis (electric resistance alternative). This is fairly obvious because the cost of solar systems on a yearly \$/Btu basis decreases faster than the increase in alternative fuel prices (NEP governed) as one's time horizon is made longer. Thus the "without" and "with" comparison of potential home installations and energy savings is less dramatic than with the shorter time period, and the cost to the government appears much more for a smaller increment in installations.

If moratoriums on new hookups were to become the rule everywhere across the nation by 1985, thereby assuming that natural gas as an alternative fuel becomes phased out between 1977 and 1985, the number of new homes forced to convert to either electricity or heating oil would dramatically change projections of potential home and energy savings impact in the residential space heating sector. The potential number of new homes installing solar could approach 750 thousand. If the same assumption is made for domestic hot water applications, an additional three-quarters to one million homes might be expected to install solar. Energy savings would increase dramatically in both cases, as would the costs to the government.

In the case of domestic hot water, as proposed, assuming that prices were not regulated, solar could compete on an even par with the electric resistance alternative, given our definition of economic feasibility. A very modest increase for electricity in real terms pushes the annualized cost of resistance heating beyond the cost of solar without proposed incentives under 20-year life cycle cost criteria. Total potential energy savings and possible new home installations would be almost identical to that with a constant real electricity price and solar incentives, with one major exception--there would be no cost to the government. This, of course, assumes that consumers utilize the 20-year life cycle cost analysis in making their decisions. As voiced earlier, a 10-year life

would be more appropriate, and even then consumers are likely to need a push from some incentive structure to actually make a positive purchase decision. In addition, deregulation affects all individuals adversely--whereas the combination of regulation and incentives results in the solar industry becoming the entity subsidized. Deregulation is more likely to cause a large number of lower income individuals to spend an increased amount for their home energy needs.

Retrofit costs for solar domestic hot water application average only about \$100 above that for new home installation (and in many cases there is presently no difference in quoted prices). This translates into almost the same pattern (economic feasibility) as that for new homes (Maps 13 through 16). What this means is that if everyone were to take advantage of the incentive program when economic parity was achieved (remembering the 50% fit assumption), there would be approximately 10 to 12 million homes where electric resistance is the alternative, 3 to 4 million homes where natural gas is relied upon, and around 1 million homes where heating oil is employed with solar domestic hot water installations under a 20-year time horizon. Total energy savings attributable to all solar installations over their assumed 20-year life could conceivably approach 5 quads. Cost to the government would reach \$6.3 billion. It is important to note that these estimates ignore all of the supply, labor, material, and other considerations that would likely limit such large-scale installations.

TABLE I
CONVENTIONAL ENERGY PRICES BY STATE*

State	Natural Gas \$/mcf	Heating Oil \$/gallon	Electricity c/kwh
Alabama	2.215	0.425	3.226
Arizona	2.275	0.442	4.360
Arkansas	1.707	0.378	3.012
California	1.740	0.453	3.714
Colorado	1.495	0.442	3.332
Connecticut	2.848	0.459	4.460
Delaware	2.412	0.444	4.636
Florida	2.456	0.444	4.042
Georgia	1.789	0.444	3.396
Idaho	3.207	0.442	2.182
Illinois	2.221	0.430	3.300
Indiana	2.025	0.430	3.320
Iowa	1.873	0.434	3.504
Kansas	1.345	0.434	2.882
Kentucky	2.632	0.425	2.834
Louisiana	1.435	0.378	2.766
Maine	4.494	0.459	3.604
Maryland	2.918	0.444	4.416
Massachusetts	3.306	0.459	4.530
Michigan	2.397	0.430	3.086
Minnesota	2.250	0.434	3.816
Mississippi	2.031	0.425	3.664
Missouri	1.895	0.434	3.514
Montana	1.908	0.442	2.506
Nebraska	1.658	0.434	3.092
Nevada	1.930	0.442	3.350
New Hampshire	3.502	0.459	4.654
New Jersey	3.384	0.451	5.196
New Mexico	1.692	0.442	3.304
New York	3.204	0.451	5.974
North Carolina	2.680	0.444	3.502
North Dakota	1.719	0.434	3.792
Ohio	2.018	0.430	3.660
Oklahoma	1.172	0.378	2.780
Oregon	2.933	0.453	2.104
Pennsylvania	2.693	0.451	3.922
Rhode Island	3.940	0.459	4.184
South Carolina	1.904	0.444	3.658
South Dakota	1.657	0.434	3.506
Tennessee	1.895	0.425	2.828
Texas	2.430	0.378	3.262
Utah	1.383	0.442	2.564
Vermont	3.733	0.459	4.548
Virginia	2.815	0.444	4.140
Washington	2.765	0.453	1.516
West Virginia	2.379	0.444	3.840
Wisconsin	2.416	0.430	3.488
Wyoming	1.989	0.442	2.064

*Natural gas and heating oil prices are for April 1977. Electricity prices are based upon the reported FPC Typical Electric Bills by state for January 1976 using the 300 kwh residential consumption level. These prices were adjusted to reflect April 1977 conditions.

TABLE II
SOLAR SYSTEM COSTS FOR RESIDENTIAL SPACE HEATING
(Dollars)

State	Space Heat Provided*		
	25%	50%	75%
Alabama	5572	5679	9338
Arizona	2925	3965	5693
Arkansas	3857	6462	10809
California	2723	3506	4883
Colorado	3951	6543	11039
Connecticut	4329	7718	13617
Delaware	4275	7596	13577
Florida	2399	2601	2925
Georgia	3573	5679	9338
Idaho	4127	7475	13955
Illinois	4815	9081	16614
Indiana	4599	8636	15872
Iowa	4842	9081	16547
Kansas	4302	7596	13361
Kentucky	4559	8447	15467
Louisiana	3560	5652	9135
Maine	4626	8487	15265
Maryland	4073	6948	12038
Massachusetts	4613	8420	15048
Michigan	4910	9500	17627
Minnesota	5018	9635	17816
Mississippi	3384	5153	8015
Missouri	4235	7515	13307
Montana	4424	8028	14670
Nebraska	4518	8163	14562
Nevada	3182	4653	7124
New Hampshire	5436	10863	20543
New Jersey	4343	7745	13725
New Mexico	3506	5436	8771
New York	4545	8231	14697
North Carolina	3776	6138	10188
North Dakota	4856	9270	17100
Ohio	3085	10161	19544
Oklahoma	3749	6094	10107
Oregon	3924	7097	13415
Pennsylvania	4856	9243	17114
Rhode Island	4343	7691	13563
South Carolina	3209	4721	7151
South Dakota	4329	7704	13577
Tennessee	3978	6867	11916
Texas	3330	5018	7799
Utah	4005	6975	12389
Vermont	5436	10863	20543
Virginia	4073	6921	11876
Washington	4100	7758	15534
West Virginia	4883	9351	17559
Wisconsin	4896	9432	17492
Wyoming	4154	7083	12078

*These fractions are chosen only for illustrative purposes and do not represent in most cases the optimal or least cost solar fraction. They (solar fraction) do however bracket that optimal fraction and point out rather vividly the non-linear relationship between solar fraction (collector area) and total system costs.

TABLE III
SOLAR SYSTEM COSTS FOR DOMESTIC HOT WATER*
(Dollars)

State	Fraction of Hot Water Provided		
	45%	65%	85%
Alabama	864	1183	1703
Arizona	740	974	1355
Arkansas	866	1190	1722
California	784	1051	1482
Colorado	1061	1417	1786
Connecticut	1178	1565	2095
Delaware	891	1233	1803
Florida	819	1105	1567
Georgia	864	1183	1703
Idaho	1020	1357	1821
Illinois	1173	1591	2086
Indiana	1152	1558	2049
Iowa	1142	1542	1973
Kansas	1121	1509	1915
Kentucky	937	1316	1954
Louisiana	910	1264	1854
Maine	1117	1504	1900
Maryland	869	1194	1730
Massachusetts	1192	1620	2097
Michigan	1198	1629	2184
Minnesota	1094	1469	1871
Mississippi	910	1264	1854
Missouri	1086	1457	1859
Montana	1042	1388	1797
Nebraska	1057	1415	1788
Nevada	723	945	1310
New Hampshire	1231	1680	2182
New Jersey	891	1233	1803
New Mexico	724	949	1314
New York	916	1277	1879
North Carolina	864	1183	1707
North Dakota	1028	1368	1743
Ohio	1229	1676	2350
Oklahoma	821	1111	1581
Oregon	900	1275	1973
Pennsylvania	1202	1633	2176
Rhode Island	1165	1579	2014
South Carolina	840	1142	1633
South Dakota	1036	1378	1724
Tennessee	881	1217	1776
Texas	813	1098	1562
Utah	960	1266	1618
Vermont	1231	1680	2182
Virginia	873	1202	1739
Washington	1018	1484	2168
West Virginia	1301	1786	2397
Wisconsin	1111	1496	1941
Wyoming	1024	1362	1701

*These fractions are chosen only for illustrative purposes and do not represent in most cases the optimal or least cost solar fraction. They (solar fraction) do however bracket that optimal fraction and point out rather vividly the non-linear relationship between solar fraction (collector area) and total system costs.

TABLE IV
VALUE OF SOLAR INCENTIVES

	SPACE HEAT TAX CREDIT (\$10,000 System)		HOT WATER TAX CREDIT (\$1,800 System)	
	NEP	HOUSE	NEP	HOUSE
1977	2000	2150	600	510
1978	2000	2150	600	510
1979	2000	2150	600	510
1980	1580	2150	460	510
1981	1580	2150	460	510
1982	1210	2150	370	510
1983	1210	2150	370	510
1984	1210	2150	370	510
1985	0	0	0	0

TABLE V
MINIMUM SOLAR PRICES VS. ANNUALIZED PRICES
OF CONVENTIONAL ALTERNATIVES
(1977 \$/10⁶ Btu)

Alternative Energy Source	Albuquerque, New Mexico			Madison, Wisconsin		
	Conventional	Solar		Conventional	Solar	
		20 yr.	30 yr.		20 yr.	30 yr.
Natural Gas	3.21	8.89	6.67	4.18	8.40	6.30
Heating Oil	5.87	8.89	6.67	5.73	8.40	6.30
Electric Resistance	9.68	8.89	6.67	10.22	8.40	6.30
Heat Pumps	5.47	8.89	6.67	7.53	8.40	6.30

TABLE VI
RESIDENTIAL SPACE HEATING:
20-YEAR LIFE CYCLE COST BASIS

	Number of Homes (10 ⁶)			Energy Savings*		Government Expenditures
	Gas	Oil	Elec	BTU(10 ¹²)	BBL(10 ⁶)	\$(10 ⁶)
W/O	-	-	.125	98 (25)	16 (4)	0
W/ HOUSE	-	-	.255	219 (61)	37 (10)	363
W/ NEP	-	-	.323	240 (72)	41 (13)	449

TABLE VII
RESIDENTIAL SPACE HEATING:
30-YEAR LIFE CYCLE COST BASIS

	Number of Homes (10 ⁶)			Energy Savings*		Government Expenditures
	Gas	Oil	Elec	BTU(10 ¹²)	BBL(10 ⁶)	\$(10 ⁶)
W/O	-	-	.330	430 (72)	75 (12)	0
W/ HOUSE	-	-	.924	1066 (191)	183 (33)	1219
W/ NEP	-	-	.905	967 (178)	165 (31)	1096

*The figures in parentheses represent accumulated savings between the year of installation and 1985 for all systems portrayed under "Number of Homes."

TABLE VIII
DOMESTIC HOT WATER:
10-YEAR LIFE CYCLE COST BASIS

	Number of Homes (10 ⁶)			Energy Savings*		Government Expenditures
	Gas	Oil	Elec	BTU(10 ¹²)	BBL(10 ⁶)	\$(10 ⁶)
W/O	-	-	1.277	70 (85)	29 (14)	0
W/ HOUSE	-	-	2.272	317 (179)	57 (32)	639
W/ NEP	-	-	2.309	322 (185)	53 (34)	638

TABLE IX
DOMESTIC HOT WATER:
20-YEAR LIFE CYCLE COST BASIS

	Number of Homes (10 ⁶)			Energy Savings*		Government Expenditures
	Gas	Oil	Elec	BTU(10 ¹²)	BBL(10 ⁶)	\$(10 ⁶)
W/O	0	0	3.270	1020 (255)	175 (44)	0
W/ HOUSE	.466	.119	3.980	1424 (371)	243 (64)	1693
W/ NEP	.736	.107	3.906	1475 (395)	277 (68)	1700

*The figures in parentheses represent accumulated savings between the year of installation and 1985 for all systems portrayed under "Number of Homes."

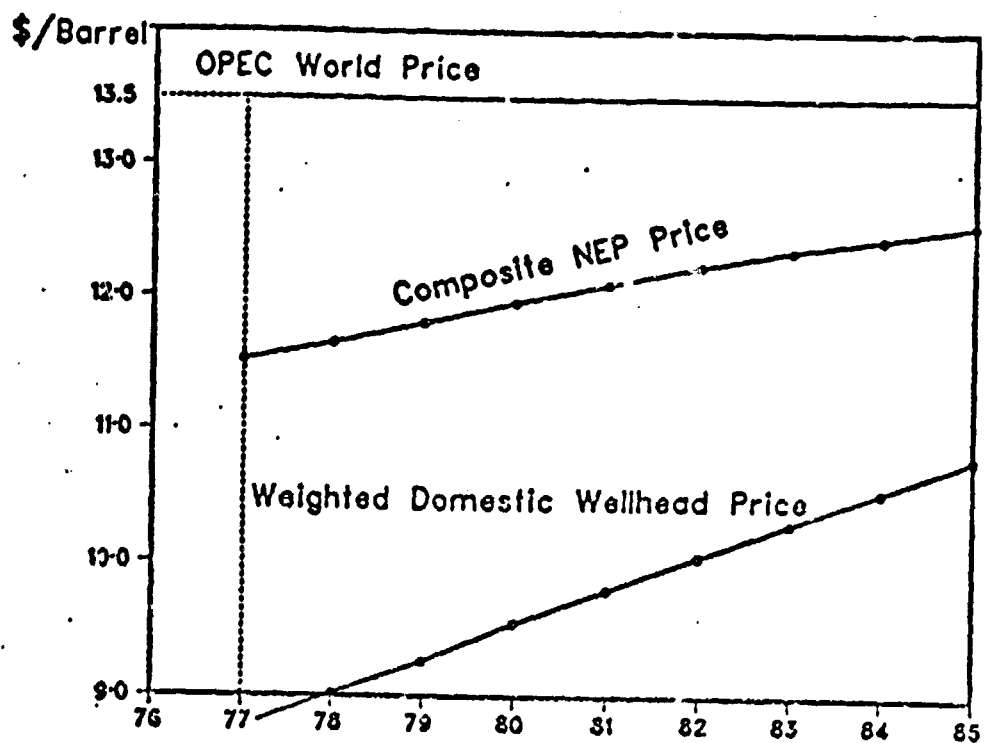


Fig. 1. Crude oil wellhead prices (1977 dollars)

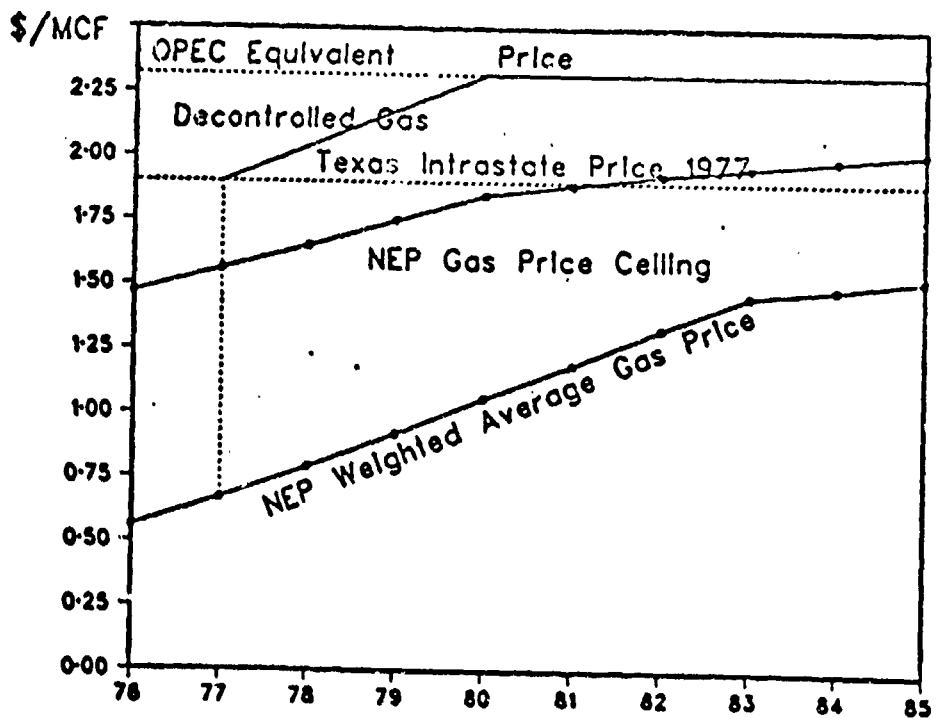


Fig. 2. Natural gas wellhead prices (1977 dollars)

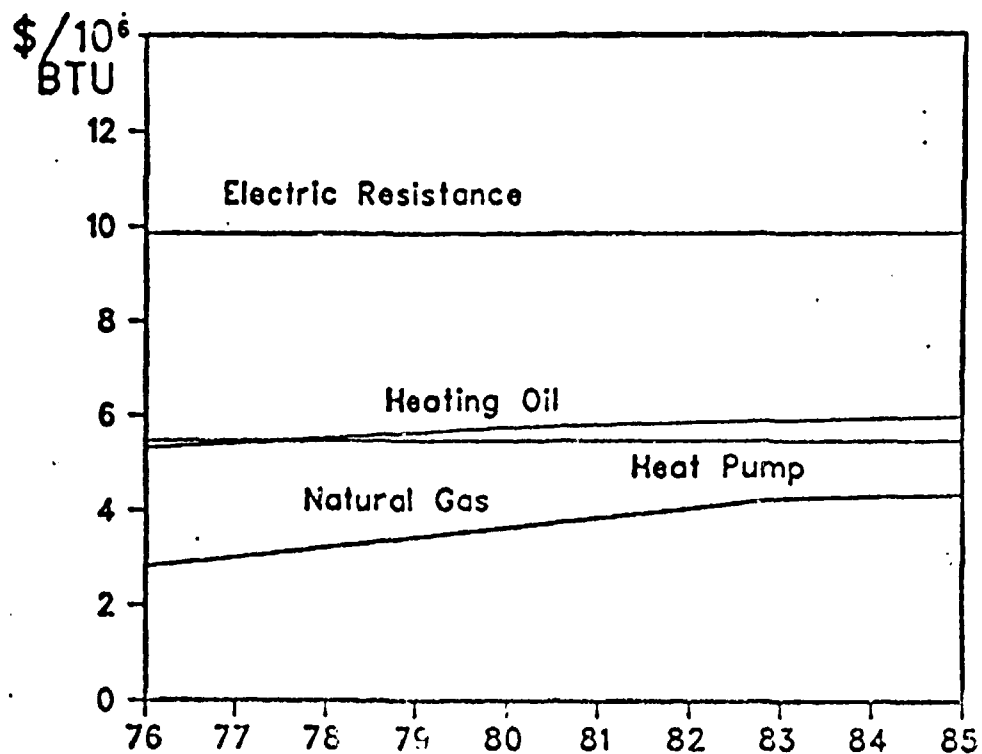


Fig. 3. Delivered costs of energy to Albuquerque, New Mexico (1977 dollars).

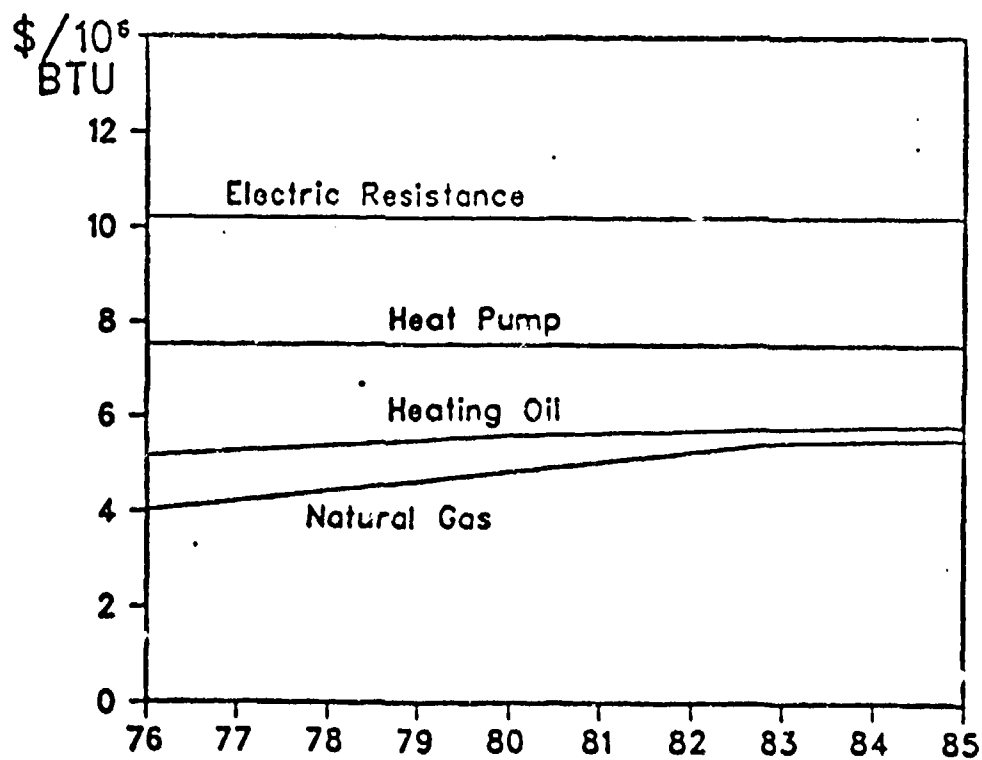
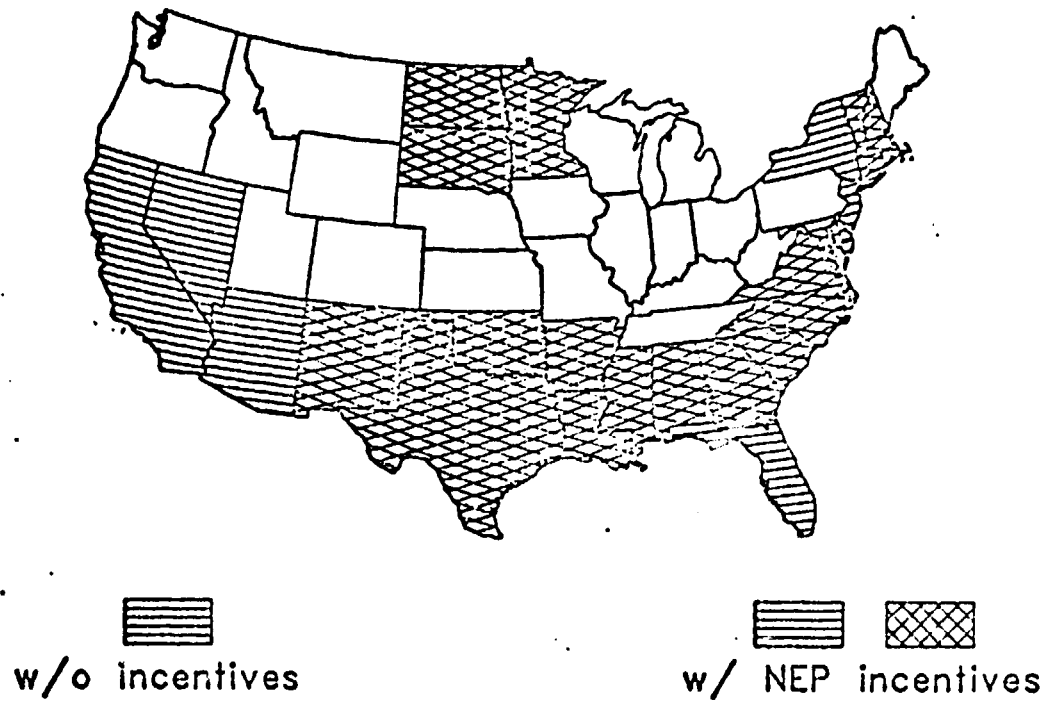


Fig. 4. Delivered costs of energy to Madison, Wisconsin (1977 dollars).

MAP 1

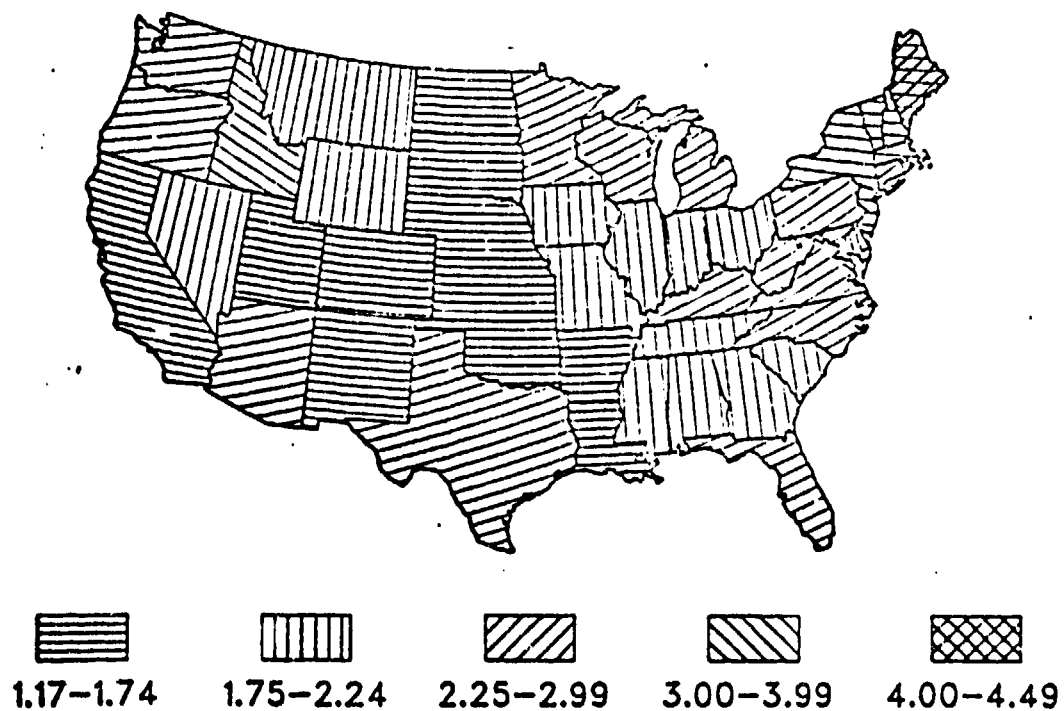
ECONOMIC FEASIBILITY FOR SOLAR DOMESTIC HOT WATER:
WITH AND WITHOUT INCENTIVES (HOUSE VERSION)

(10-Year Life Cycle Cost Basis)

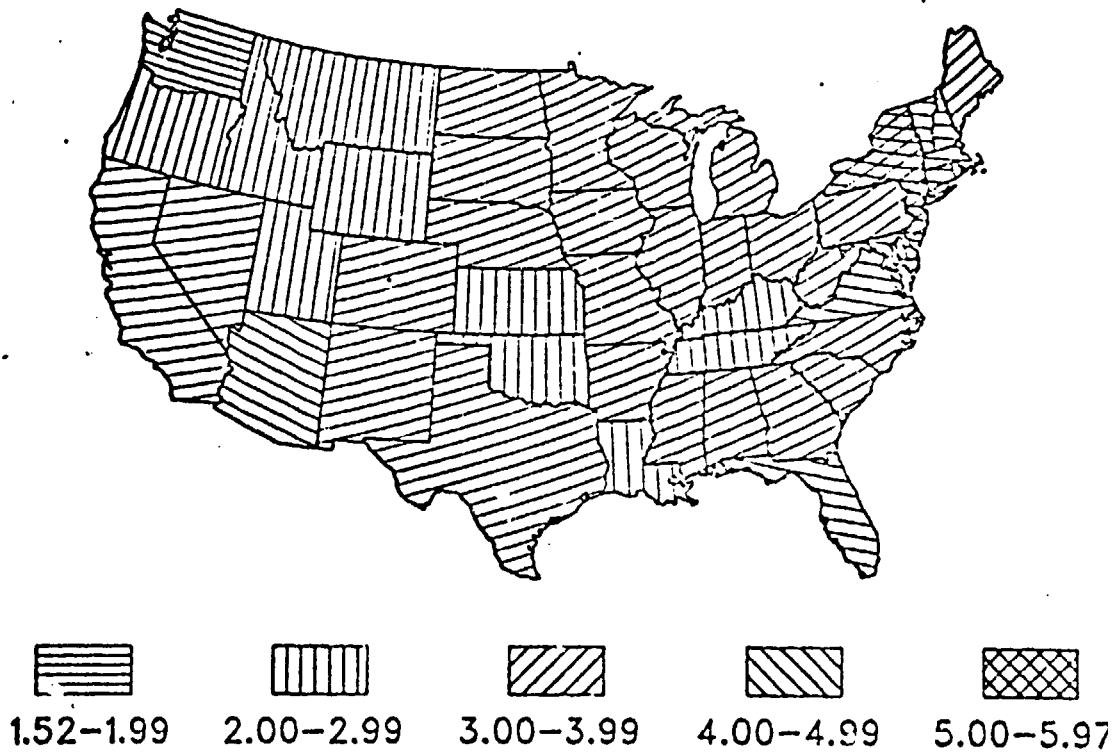


MAP 2

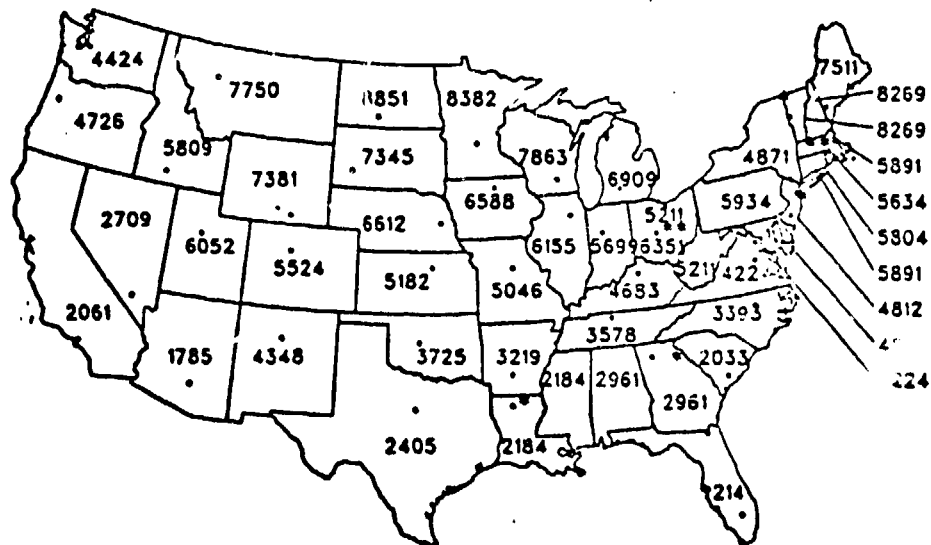
1977 RESIDENTIAL GAS PRICES
(Dollars Per mcf)



MAP 3
1977 RESIDENTIAL ELECTRICITY PRICES
(Cents Per kWh)

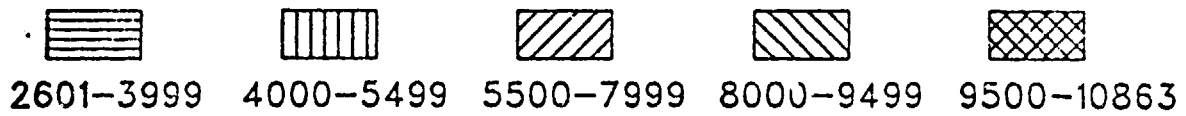
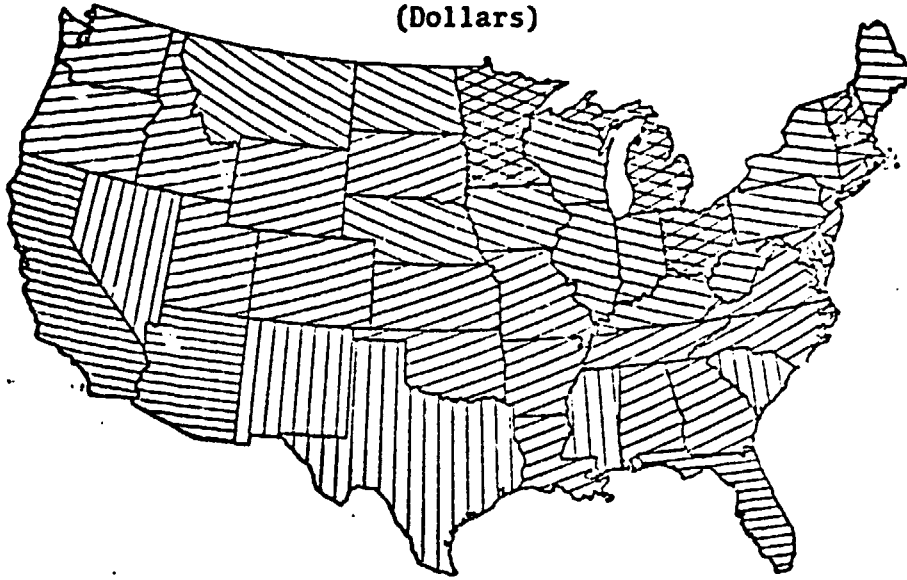


MAP 4
CITIES AND HEATING DEGREE DAYS



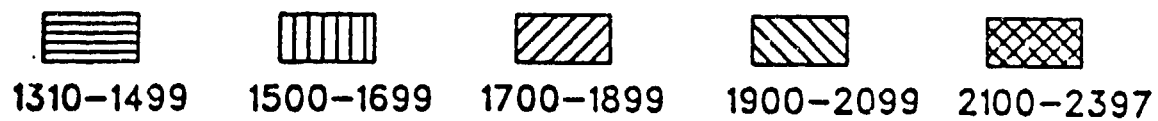
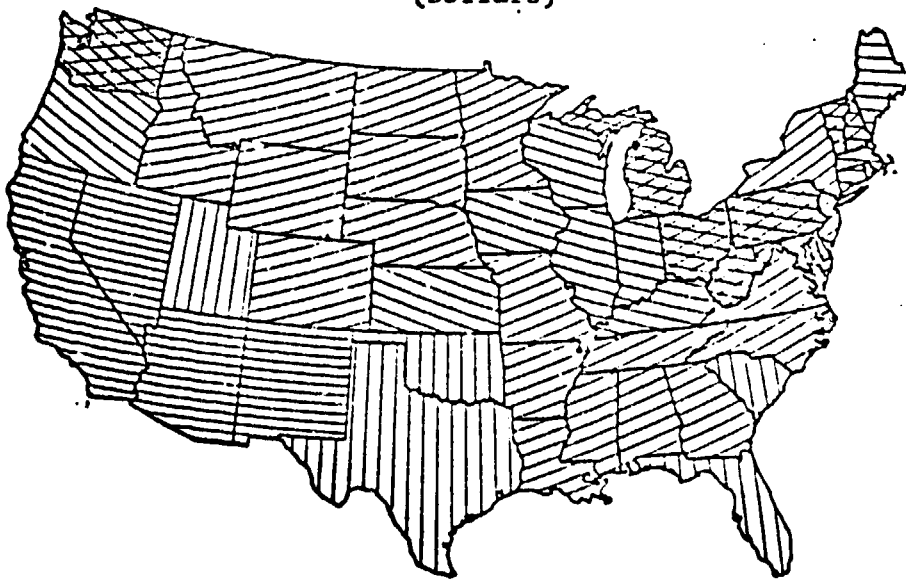
MAP 5

SOLAR SPACE HEATING SYSTEM COST:
SOLAR FRACTION 50%
(Dollars)

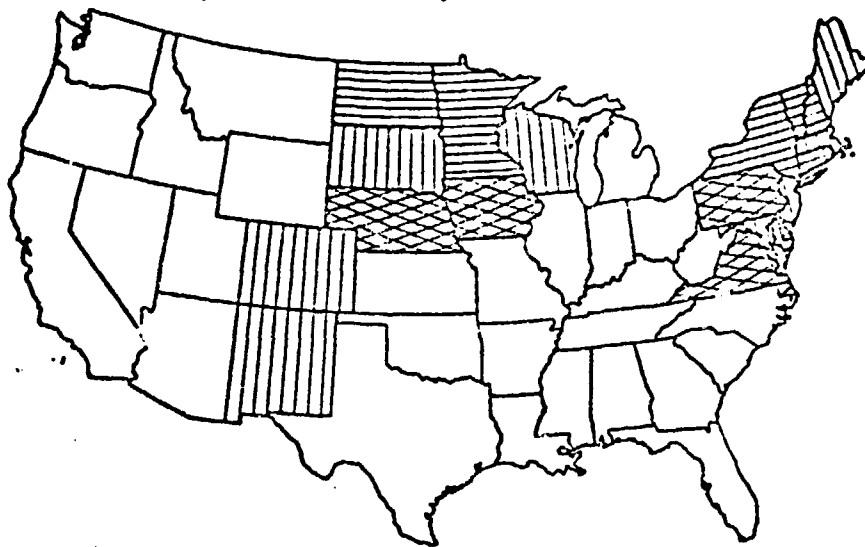


MAP 6

SOLAR DOMESTIC HOT WATER SYSTEM COST:
SOLAR FRACTION 85%
(Dollars)

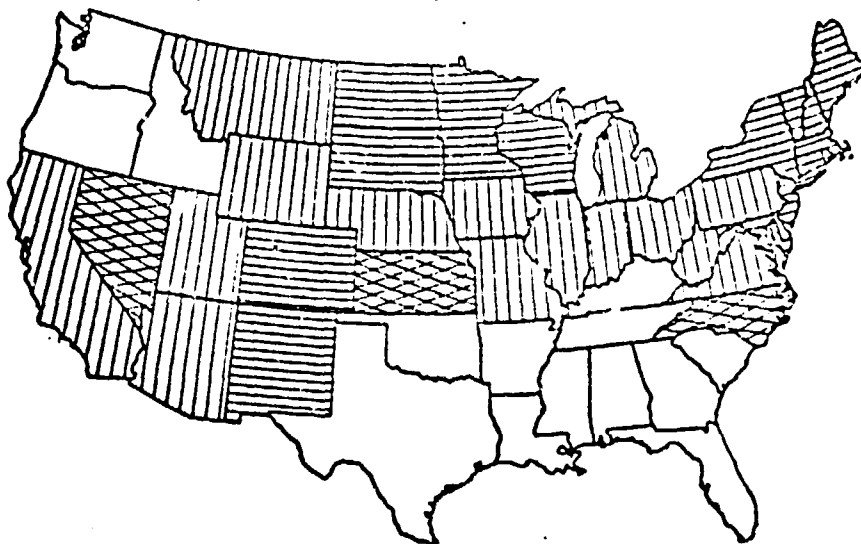








**SOLAR FEASIBILITY FOR RESIDENTIAL SPACE HEATING:
ALTERNATIVE SYSTEM - ELECTRIC RESISTANCE
(20-Year Life Cycle Cost Basis)**



MAP 8

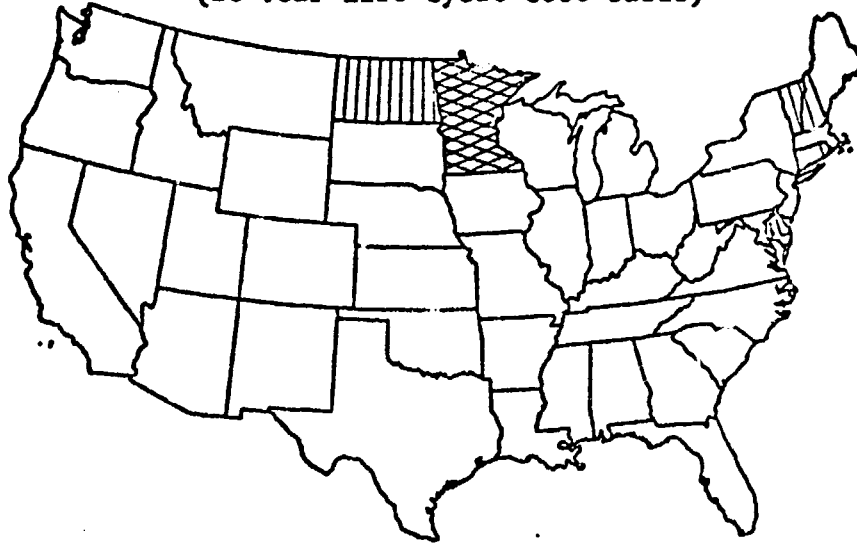
**SOLAR FEASIBILITY FOR RESIDENTIAL SPACE HEATING:
ALTERNATIVE SYSTEM - ELECTRIC RESISTANCE
(30-Year Life Cycle Cost Basis)**









 w/o incentives
  w/ House incentives
  incentives
  w/ NEP incentives
 


MAP 9

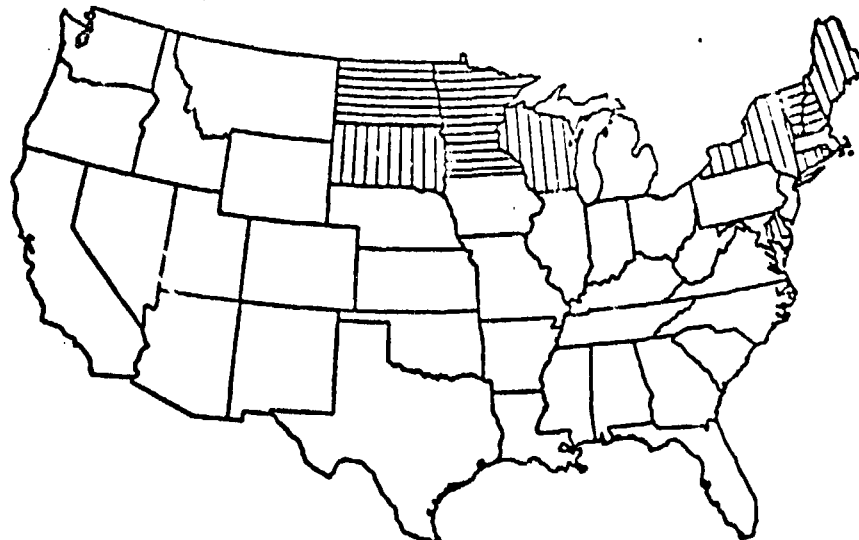
SOLAR FEASIBILITY FOR RESIDENTIAL SPACE HEATING:
ALTERNATIVE SYSTEM - ELECTRIC HEAT PUMPS
(20-Year Life Cycle Cost Basis)









 w/o incentives
   w/ House incentives
    w/ NEP incentives

MAP 10

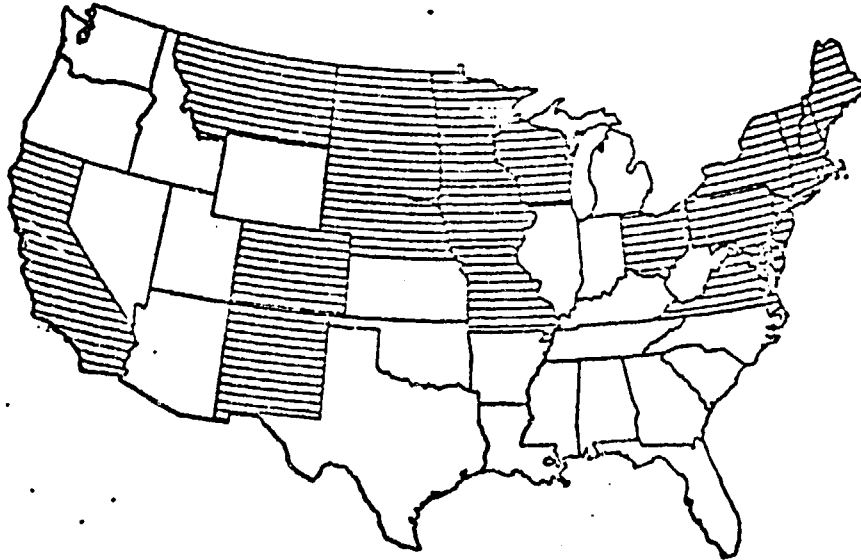
SOLAR FEASIBILITY FOR RESIDENTIAL SPACE HEATING:
ALTERNATIVE SYSTEM - ELECTRIC HEAT PUMPS
(30-Year Life Cycle Cost Basis)



 w/o incentives
   w/ House incentives
    w/ NEP incentives

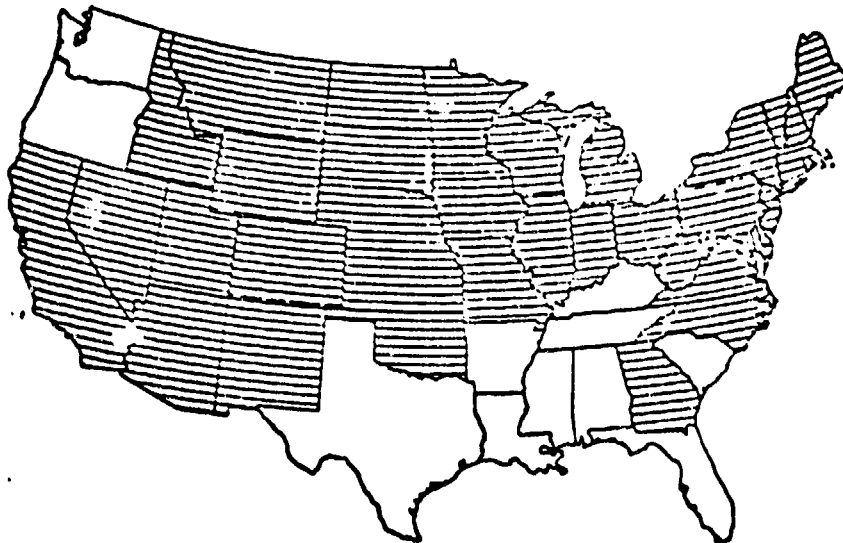
MAP 11

SOLAR FEASIBILITY FOR RESIDENTIAL SPACE HEATING:
ALTERNATIVE SYSTEM - ELECTRIC RESISTANCE
(ENERGY PRICES DEREGULATED AND NO INCENTIVES)
(20-Year Life Cycle Cost Basis)



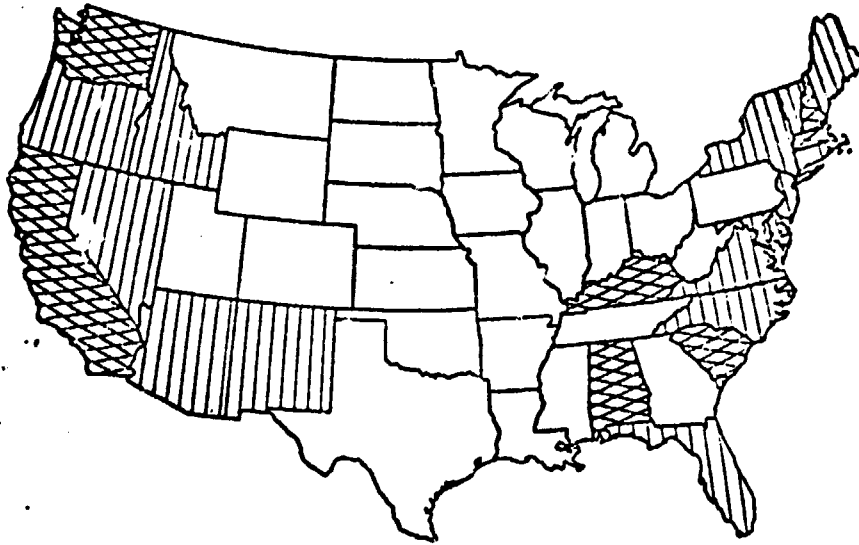
MAP 12







SOLAR FEASIBILITY FOR RESIDENTIAL SPACE HEATING:
ALTERNATIVE SYSTEM - ELECTRIC RESISTANCE
(ENERGY PRICES DEREGULATED AND NO INCENTIVES)
(30-Year Life Cycle Cost Basis)



MAP 1.

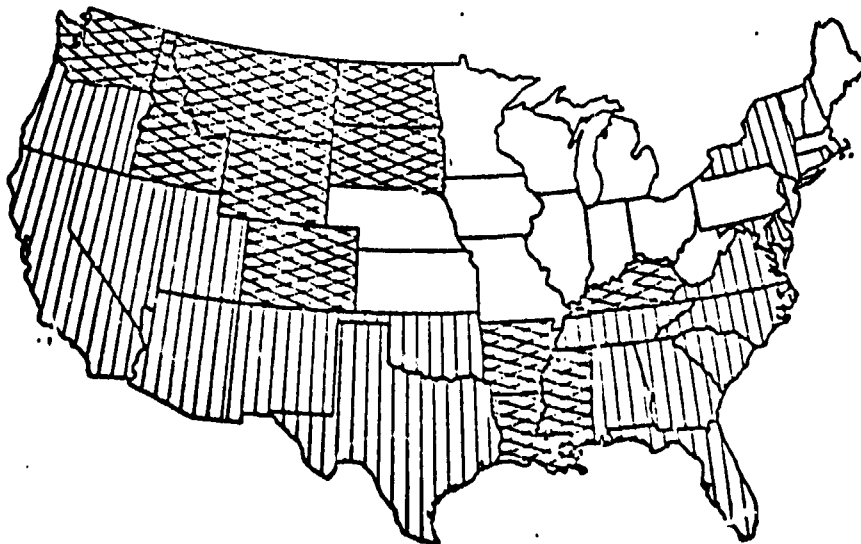
SOLAR FEASIBILITY FOR DOMESTIC HOT WATER:
ALTERNATIVE SYSTEM - NATURAL GAS
(20-Year Life Cycle Cost Basis)




 w/o incentives   w/ House incentives    w/ NEP incentives

MAP 14

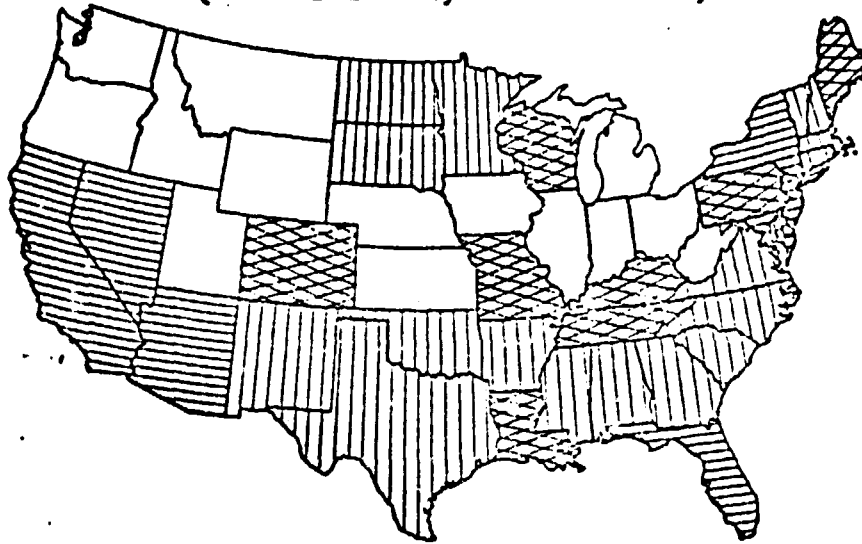
SOLAR FEASIBILITY FOR DOMESTIC HOT WATER:
ALTERNATIVE SYSTEM - HEATING OIL
(20-Year Life Cycle Cost Basis)

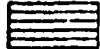




 w/o incentives   w/ House incentives    w/ NEP incentives

MAP 15

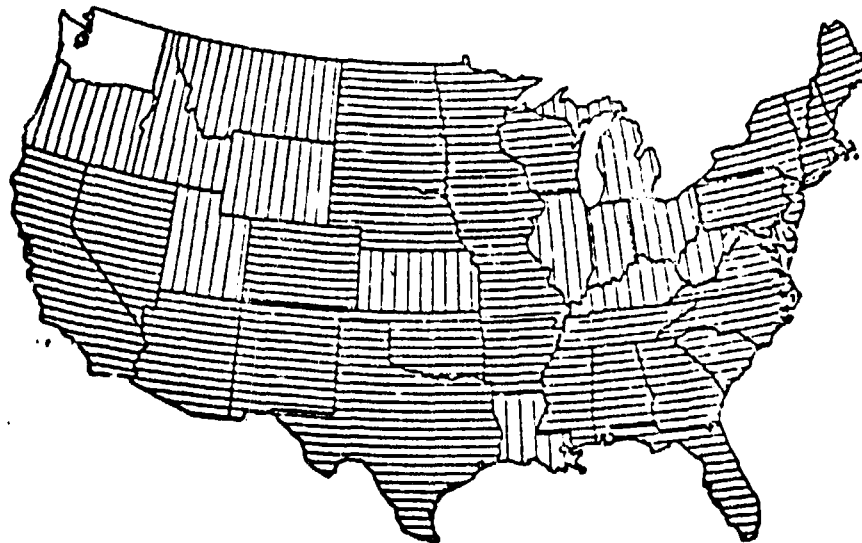
SOLAR FEASIBILITY FOR DOMESTIC HOT WATER:
ALTERNATIVE SYSTEM - ELECTRIC RESISTANCE
(10-Year Life Cycle Cost Basis)


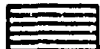



 w/o incentives
  w/ House incentives
  w/ NEP incentives

MAP 16

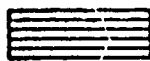
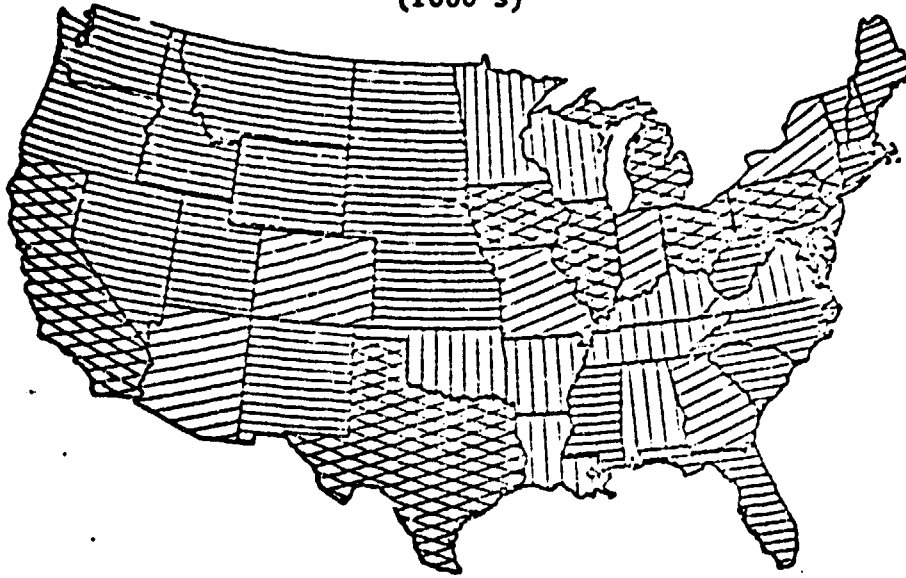
SOLAR FEASIBILITY FOR DOMESTIC HOT WATER:
ALTERNATIVE SYSTEM - ELECTRIC RESISTANCE
(20-Year Life Cycle Cost Basis)



 w/o incentives
  w/ House incentives
  w/ NEP incentives

MAP 17

PROJECTED TOTAL NEW HOMES 1977-1985
UTILIZING NATURAL GAS FOR SPACE HEATING
(1000's)



1-49



50-99



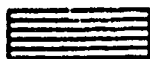
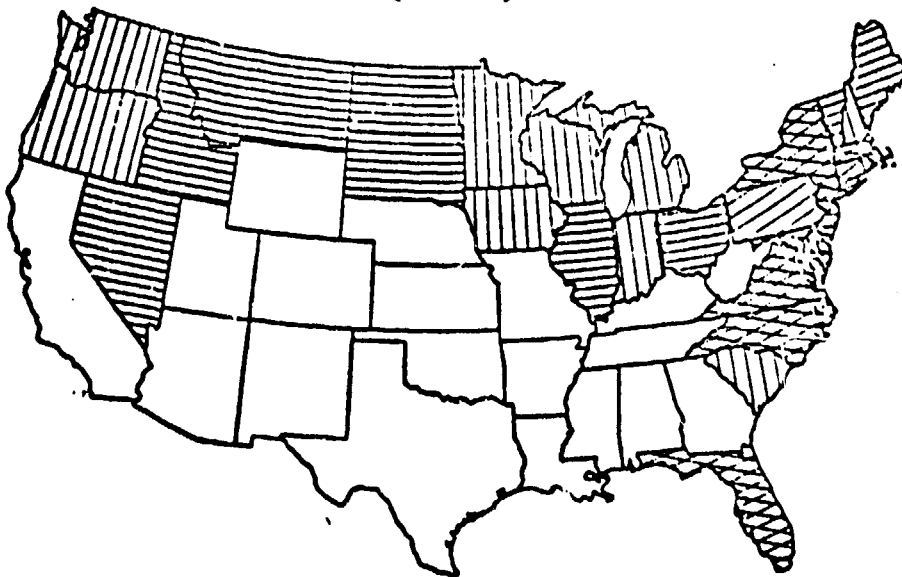
100-199



200+

MAP 18

PROJECTED TOTAL NEW HOMES 1977-1985
UTILIZING HEATING OIL FOR SPACE HEATING
(1000's)



1-24



25-49



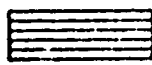
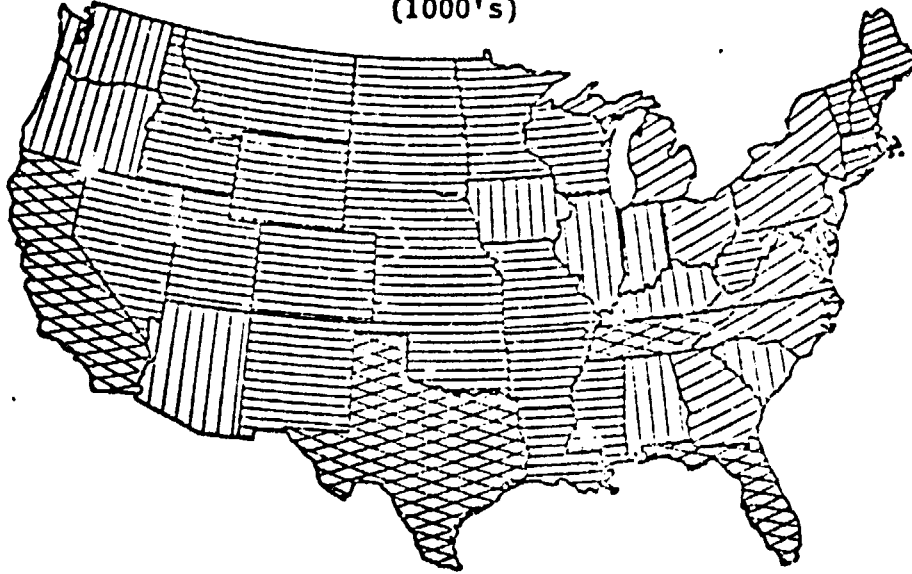
50-74



75+

MAP 19

PROJECTED TOTAL NEW HOMES 1977-1985
UTILIZING ELECTRICITY FOR SPACE HEATING
(1000's)



1-49



50-99



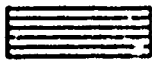
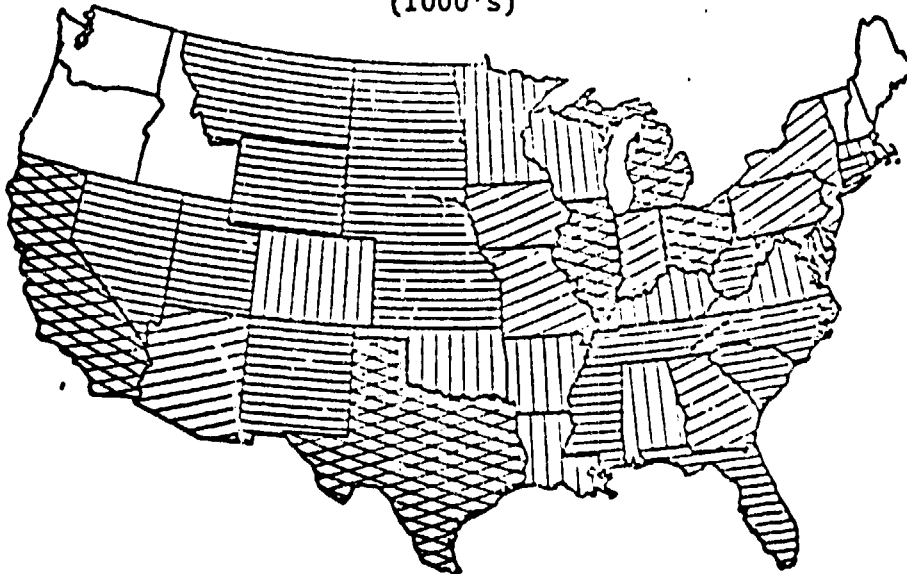
100-199



200+

MAP 20

PROJECTED TOTAL NEW HOMES 1977-1985
UTILIZING NATURAL GAS FOR DOMESTIC HOT WATER HEATING
(1000's)



1-49



50-99



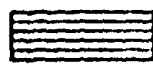
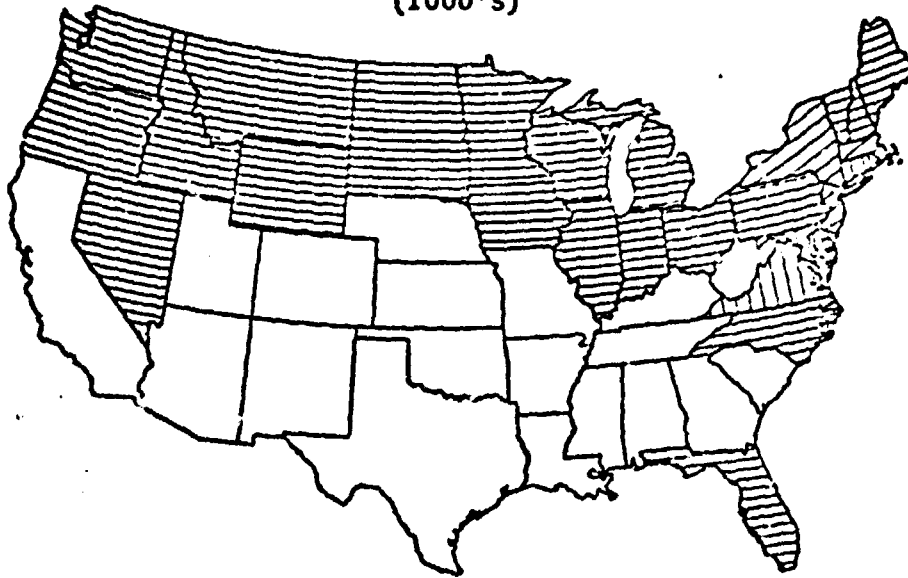
100-199



200+

MAP 21

PROJECTED TOTAL NEW HOMES 1977-1985
UTILIZING HEATING OIL FOR DOMESTIC HOT WATER HEATING
(1000's)



1-24



25-49



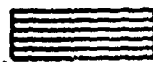
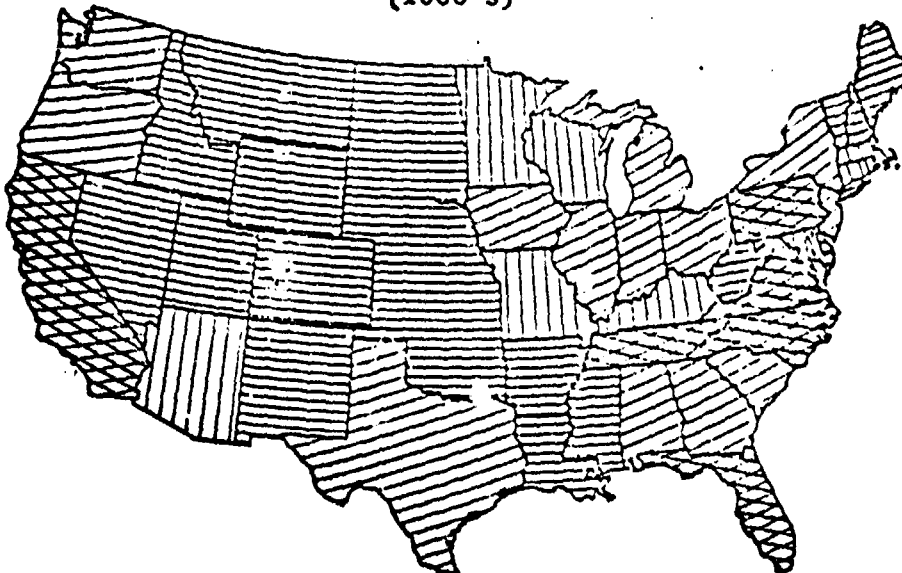
50-74



75+

MAP 22

PROJECTED TOTAL NEW HOMES 1977-1985
UTILIZING ELECTRICITY FOR DOMESTIC HOT WATER HEATING
(1000's)



1-49



50-99



100-199



200+

APPENDIX A
PERFORMANCE AND COST OF SOLAR HEATING SYSTEMS[†]

This Appendix describes performance and cost parameters for the two most promising and best known short run uses of solar energy--domestic hot water and space heating of residences.

The solar energy incident on the outside of a building can be used to provide a major fraction of space heating and domestic hot water requirements in large portions of the United States. A solar heating system generally consists of solar collectors to absorb the sun's heat energy and a heat storage medium to hold excess heat for release during periods when the sun does not shine. Since weather, solar insolation, and energy cost patterns vary significantly from place to place it is desirable to base the design of a solar system on the local situation.

Although the operation of a solar system can be readily understood in a qualitative fashion, the quantitative analysis of a system (e.g., sizing of collector array) involves computer simulation of solar performance using actual hour by hour weather data, and is considerably more difficult. A fairly general method developed at the Los Alamos Scientific Laboratory (LASL) was employed to supply the necessary quantitative analysis.[§] LASL developed standard parameters for both residential space heating systems and for domestic hot water systems which serve as the basis for the performance simulation work being done at Los Alamos and for the economic analysis reported in Section III.

The first section briefly defines performance characteristics of the baseline collectors used for this study. Section two develops the price estimates used for the collector systems and compares them to other systems on a total installed cost basis.

[†]This appendix is based in part on material developed for and presented in "The Economics of Solar Home Heating," prepared by the same authors for the Joint Economic Committee of Congress (JEC) in March 1977.

[§]Balcomb, J. Douglas and Hedstrom, James C., "A Simplified Method for Sizing a Solar Collector Array for Space Heating," Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

Performance Parameters

The first consideration in the thermal design of the building should be to minimize the load within the constraints imposed by economics and architecture. The thermal load is defined as the total heat required by the building per day per degree fahrenheit temperature difference between the inside temperature and the outside temperature (frequently expressed in units of BTU/Degree-Day). For a small, single story, well insulated building, the thermal load should be in the range of 10 BTUs per degree day per square foot of floor area (BTU/DD/Ft²). It is important to minimize the building load through adequate insulation, double glazing, control of infiltration, and passive control of the solar gains since the area of solar collector required to obtain a given fraction of the heating requirements is directly proportional to the building load.

Design optimization usually involves a tradeoff between cost and performance. For most locations it is uneconomical to design solar heating to provide for 100% of the heating requirements because of the necessarily large collector area and storage volume that would be required. A solar system should always be designed with a full capacity auxiliary heating unit for periods of extended cloudiness. At some point the extra performance which can be achieved by adding more equipment or material will exceed the savings incurred. This is true of extra insulation, extra collector area, and many other design variables.

There are two common categories of solar space heating collectors: those that use air-heating collectors and those that use water- or liquid-heating collectors. An engineering evaluation indicated that the air-heating collector systems (commonly called "air systems") probably have a slight advantage over liquid heating collectors for 20 to 30 year residential applications because they are lighter, easier to fabricate, tolerant of minor leaks, less likely to have corrosion problems, and do not need freeze protection. Preliminary analysis of both air and liquid systems showed that the economic feasibility of the two types of systems were essentially the same. Thus, only air systems were analyzed in detail, but the results are applicable to both air and liquid systems. Domestic water heating systems were analyzed separately from space heating systems, even though an "optimal" space heating system will almost always include an integral domestic water heater. This was done to clearly illustrate the different economic characteristics of these two applications. Since a liquid-to-water heat exchanger is generally more efficient than an

air-to-water exchanger, a liquid collector for domestic water heating was assumed in this study. The air heating collector system used in this analysis is depicted in Figure A1. In this system, air passes through channels in the collector, is heated, and the heat is transferred to a heat storage system and/or directly to the house. Air has a low heat transfer coefficient, but air-heating collectors can be properly designed to have adequate performance.

The common thermal storage medium for air heating collectors is a bin full of rocks which is heated by the hot air from the collector. Space heating is accomplished by blowing cooler air from the room through either the heated rock-bin or directly through the collector itself. If room temperature falls below a chosen level, an auxiliary space heater is used to maintain room temperature.

In most common air/rock systems the air flow direction through the rock bin is reversed between the charging and discharging storage. This makes optimum use of thermal gradients in the rock bin and allows more efficient use of a given quantity of rocks. One method of providing this reverse flow is as shown in Figure 1. The system requires only one fan and two double-dampers. When the collector temperature exceeds the rock bed exit temperature (left side), the collector is on and Damper C is in the position shown. Otherwise, the collector is off and Damper C is in the upper position.

When the building requires heat, Damper H is in the position shown. Otherwise, Damper H is in the upper position. The furnace is operated when necessary to satisfy the building load. The fan is on when either the collector is on or the building needs heat.

When the collector is on, the solar heated air is routed either to the building space directly (when the building needs heat) or to the rock bed. When the collector is off, the building is heated by blowing air through the rock bed in the reverse direction and directly into the building space. The standard air system parameters developed by LASL are given in Table A1.

Domestic solar water heaters are attractive because they work year round and can usually be retrofitted to existing dwellings. Compared to space heating, they supply a relatively constant load and others can be sized for more uniform and efficient use of the solar collector array and storage tank. The hot water demand profile shown in Figure A2 was assumed for this study based on personal experience and estimation. The simulations were run assuming that the profile was the same for every day of the year.

As mentioned above, liquid cooled collectors enjoy a natural advantage where only domestic hot water is generated, since no air-to-liquid transfer required anywhere within the system. On the other hand, simpler, less expensive liquid-to-water heat exchangers are desirable so that antifreeze and corrosion inhibitors can be circulated through the collector. The assumed system that incorporates these features is shown in Figure A3.

The nominal design parameters for the collector are given in Table A2. Since the storage tank is relatively small, the heat loss from the tank surface is relatively larger than for a space heating system and is explicitly accounted for in the analysis. A tank surface of $0.5 \text{ ft}^2/\text{ft}_c^2$ is assumed with a tank insulation heat loss coefficient of $.083 \text{ BTU}/^\circ\text{F}\text{-hr}\text{-ft}_c^2$.

For the two-tank system, depicted in Figure A3, the solar-heated storage tank acts as a source of preheated water for the second tank, a conventionally fired, domestic hot water tank. A control scheme was adopted in which auxiliary heat is added to the second tank as necessary to maintain the storage temperature at 120°F . A nominal thermal storage heat capacity was chosen for the solar storage tank equal to 15 pounds (1.8 gallons) of water per square foot of collector. For the second, auxiliary-fired tank, a nominal capacity equal to one-half the daily usage was chosen. In this analysis the daily hot water usage is 80 gallons per day; therefore, the second storage tank is 40 gallons.

The two-tank domestic hot water system can be expected to perform at higher overall efficiency than a one-tank system. Since the auxiliary heat is supplied at the second tank, not at the solar heated tank, the solar heated portion of the two-tank system can operate at a lower storage (and hence collector) temperature and higher heat collection efficiency. By proper adjustment of the solar storage tank temperature, the overall efficiency of the two-tank system can be raised over that of the one-tank system.

For various selected cities across the continental U.S., the LASL simulation program was exercised to determine the square footage of collector needed per specified fractions of solar heat provided. The residential space heating system was as portrayed in Figure A1 with performance parameters as defined in Table A1. The domestic hot water system was as portrayed in Figure A3 with performance parameters as defined in Table A2.

Cost Parameters

The cost of solar energy systems can and has been computed by a variety of generally accepted methodologies. These costs, when contrasted with projected prices of alternative energy systems, give the investigator a picture of potential solar penetration in various regional markets. This section is concerned with constructing realistic cost estimates of a solar domestic hot water system and a solar air heating system designed solely to meet some fraction of a residence's (single-family detached for this study) hot water or space heating demand over a normal year.

There exists today very little hard data on the cost of solar energy systems designed solely for residential space heating. The systems available now are usually designed and delivered with at least a hot water pre-heater⁺ and most components of the backup or auxiliary heating system. In addition, the systems are generally site specific; that is, there are large design, engineering, and supervision costs inherent within the installed system. In addition, initial unit fabrication costs and the training required for proper installation increase total system costs significantly.

On the other hand, there does exist more information on the cost of solar energy systems designed solely for domestic hot water heating. The systems available now are usually designed with one or more collector panels in conjunction with the hardware (pump, pipe, heat exchanger, and controls) and auxiliary storage tank. In most instances these systems are not particularly site specific: that is a common package⁵ is installed in varying locations, with

⁺It is recognized that an integrated solar system designed for hot water and space heating purposes will almost always be more competitive and hence closer to an "optimal" total energy system within a single family residence than one designed solely for space heating. To keep the analysis to a minimum, however, space heating and hot water heating will be examined separately.

⁵These packages do vary in sizing, but usually in discrete increments. For climatic conditions that differ within specified range, equivalent packages are generally installed in the two locations. This usually leads to the solar fraction being, say, 65% in one location, 75% in the other. Only when the solar fraction drops below a certain level is an additional panel added to the overall hot water package.

the fraction of total hot water heating load supplied by these equivalent systems varying due to weather conditions and input water temperature. However, for this study we allow collector sizes to vary in a continuous fashion for every site so that a continuum of solar costs can be computed.

On the basis of the design parameters in the previous section, cost data were obtained from many individuals and firms in the U.S. engaged in designing engineering, marketing and installing solar energy systems. In addition, some preliminary information was obtained from both the ERDA and HUD solar demonstration programs. Various measures of costs[†] were reported to us, and after transformation into measures used in this study (total installed system dollar costs and dollars per 10^6 Btu of heat delivered) were reviewed. Although there was much disagreement among the various estimates (with much of that disagreement attributable to either system design or system location), the general consensus was that total fixed costs, those costs independent of storage and collectors, would run approximately \$2250 for residential space heating and \$350 for domestic hot water systems.

Some explanation of the above costs should help to clarify those figures. As stated in the previous section on solar performance, an air system was employed for space heating purposes, a liquid system for hot water application. In an air system, insulated duct and an air handling system (fan, dampers, sensors, controls, etc.) make up those components not likely to be very much different (collector independent) for systems around the country.[§] Therefore, for our 1500-square-foot, relatively well insulated home, a fairly uniform air handling control system could be employed; and with proper design a fairly uniform quantity of additional (over and above that required for conventional heating systems) insulated duct work would be possible around the U.S. For the liquid system use in hot water applications, fairly standard sized pumps, heat exchangers, pipes, sensors, and controls could be used in most of the U.S. These components would be almost independent of the square footage of collector, and therefore were assumed to make up the collector-independent cost component.

[†]These measures being dollars per square foot of collector, dollars per heating season or year, system costs net of savings during some specified period, and dollars per heated area of house in addition to the two measures utilized in this study: total installed system costs and dollars per 10^6 Btu.

[§]Conventional track homes where installation of the required duct work and air handling control system is commonplace.

In addition to the material components themselves, relatively common installation practices were believed to be associated with both the air and liquid systems. With some assumptions about skill type and level requirements, union and non-union rules, and wage rate differentials among regions of the U.S., collector-independent labor costs were computed for each state. These estimated costs were compared to known values where possible, and subsequently modified to reflect present regional differences.

In most states when the assumption of labor practice commonality was combined with the assumption of uniform f.o.b. equipment prices, very similar total collector-independent costs were derived for each state. Because the costs are only estimates of probable future systems, a single dollar figure was chosen to represent all of the states: that of \$2250 for residential space heating and \$350 for domestic hot water applications, respectively. [More will be said on the validity of these two dollar figures after discussion of collector and storage costs.]

From the same data and information sources mentioned above, costs were established for the other major component (collector-dependent) of a solar system: that is, the collectors, supporting framework, and storage requirements. It is in the area of collector design and performance where the most controversy occurs.[†] However, by utilizing a baseline collector design, general agreement was obtained on probable costs. Because an air collector is relatively simple when compared to a liquid collector, its cost per square foot will be significantly less. Structural supports and mounts should differ only slightly for the two collectors, while the storage costs (on a square foot of collector basis) would be expected to diverge because of the nature of the storage medium: water for the liquid system and rocks for the air system.

Following the same line of argument (and procedure) as that presented for collector-independent costs,[§] the following installed costs were established for the collector-dependent component of a solar system: \$16.50 per square foot of collector for a liquid system, and \$13.50 per square foot of collector for an

[†]In a following discussion, this controversy will be used to help evaluate the system costs established for this study.

[§]Commonality of labor practices (skill type and levels, union penetration, and wage rate differentials adjusted for productivity differences) and uniform f.o.b. equipment prices.

air system. A simple baseline single glazing collector (liquid type) supported by common mounts with an associated water storage tank (.21 gallons of storage per square foot of collector) was used for the liquid system cost computation. For the air system cost computation, a simple baseline single glazing collector (air type) supported by common mounts with an associated rock storage bin was used. Most of the cost difference between the two can be associated with either the collector or storage equipment itself.

Using these uniform (across states) cost estimates in conjunction with the square footage of collector requirements established from the LASL performance code, total systems costs were derived in terms of 1977 dollars. [These costs by state for representative solar fractions were presented in Section III.] Because we have already accounted for some potential reductions in costs (i.e., economies of scale for the marketing and transportation of common equipment, and the establishment of common installation practices), the real costs of solar systems were assumed to remain constant through the period of analysis--1978 through 1985.

The final cost component of solar energy systems included in this analysis is the annual operation and maintenance (O & M) expenses over an air system's expected twenty to thirty year life for residential space heating, and ten to twenty year life for domestic hot water system. Because so little is actually known about possible maintenance, repair, and replacement costs for the various components of a solar system, large expenditures were allowed at certain intervals and towards the end of the life cycle. Summing the expenditures over the expected life and computing a yearly average gives an estimate of annual operation and maintenance costs of 0.75% of total system costs for the residential space heating air system, and 1.0% for the domestic hot water system.

Before moving to a brief discussion of the validity of these cost estimates, two tables are presented which contain some actual computations for select cities. Table A3 displays these computations for residential space heating, Table A4 for domestic hot water. Heating degree days are included in Table A3, for the yearly heating load are directly proportional to those figures, while the hot water heating load is assumed constant for all sites. Some of the sites displayed are the same ones commonly used in other economic studies.

Several things about each table should be noted. First, for residential space heating, although the heating degree days (potential heat load) vary little between Albuquerque, New Mexico, and Seattle, Washington, the square feet of collector required to meet 50% of the standard home's heating load (50% solar fraction) is significantly different. At the same time, in Madison, Wisconsin, the heating degree days are almost four times those for Charleston, South Carolina with the square footage of collector requirements varying by less than a factor of three. As well known and expected, weather conditions (amount of sunshine available when needed) play a formidable role in total system costs.

Second, with collector-independent costs being equal for all sites, those sites with lower heat loads (heating degree days) have to bear a heavier burden on a Btu equivalent basis from those costs. That is, in Charleston, South Carolina, the insulated duct work and air handling control system comprise close to 50% of the total system costs, whereas in East Wareham, Massachusetts (near Boston), these same costs make up only slightly more than 25% of total system costs. This points out why on a dollar-per-Btu basis those areas with a relatively low total heating need would not choose to install solar.[†]

Third, because hot water is needed year round, less divergence on system costs (and collector areas) is evident than for residential space heating among the representative sites. Whereas, for space heating in Madison, Wisconsin, solar costs are about 75% higher for a 50% solar fraction than in Albuquerque, New Mexico, for domestic hot water there is less than a 50% difference in costs for an 85% solar fraction.

Fourth, the impact of the sunbelt is quite evident in both space heating and hot water applications of solar energy. Albuquerque, New Mexico, requires significantly less collector area to provide a given quantity of hot water (58 versus 78 square feet), while at the same time requiring only 30% more collector area to provide almost double the space heating needs.

Fifth, the importance of the collector-independent cost component is diminished in the domestic hot water application of solar energy. In concert

[†]For example, although Phoenix, Arizona, does have need of heat during the winter months on select occasions, it would probably not be anywhere close to cost effective to employ solar to supply those needs. The quantity of heat needed would not justify a solar system even though only a few collector panels (and hence only minimal dollar cost for this component) might be required. The dollar cost per 10⁶ Btu would be for higher than most conventional means of supplying that heat due to the \$2250 expenditure even before adding the collector costs.

with year round requirements for hot water, this diminished importance leads to much more weight being given collector costs in the economic feasibility analysis.

As stated several times earlier, there are a number of ways that solar systems can be priced. This usually leads to confusion when trying to compare systems. In addition, various rules-of-thumb have oftentimes been established to estimate future costs, thereby further complicating comparisons. We nevertheless will briefly discuss apparent differences between cost estimates derived from the current data[†] of solar system prices and those (cost estimates) constructed for this study.

Once solar system costs are adjusted so that a constant solar fraction is being priced, most estimates of current costs are remarkably similar for flat-plate collector designs. Wherever possible, individual estimates or actual quoted prices were transformed into a total installed system cost for the representative solar fractions reported in Section III (these being 25, 50, and 75 per cent solar for residential space heating and 45, 65, and 85 per cent solar for domestic hot water). This made the comparisons much easier, and does allow us to contrast potential prices through probable ranges of solar fractions. For the most part, the system costs employed in this study were somewhat lower than current estimates. However, around the "optimal" solar fraction as computed in this study (varies by state), less than a 15% differential was usually evident between those costs presented in Tables II and III and the upper range of current system costs. We therefore conclude that for flat-plate collector designs the costs used here are certainly realistic. Current costs in real terms should decrease somewhat as engineering, design, marketing, and transportation costs are lowered (economies of scale) due to solar penetration. However, a drastic drop in solar system costs is not believed possible for the following reasons.

First, in typical installations, the collectors account for only 20% of total system cost. Since most of the other components of a solar system (i.e.,

[†]Actual estimates or the supporting data will not be reported here. Much of the information is in a form that does not easily lead to results compared here. In addition, some of the data collected was by brand name, and therefore does not lend itself to publication in this type of study.

pumps, pipes, sensors, etc.) are already mass produced and readily available, there is little chance that mass produced solar collectors could substantially lower total installed costs. Second, the cost of quality solar equipment over the last several years has been increasing at a faster pace than general construction costs or the cost of living. Although there are many factors at work, we believe the key ones to be (a) inclusion of warranty and call-back costs, (b) design changes that have increased reliability significantly, (c) increase in the costs of copper, aluminum, and other materials, and (d) inclusion of profits that were deleted earlier for advertising and market penetration purposes. Third, the overall performance of most systems is not likely to equal advertised claims or computer simulation results. As this begins to be accounted for in system sizing, more collector area for a given solar fraction will be necessary. Fourth, durability and reliability of solar systems for 20 or 30 years will not be a trivial task. As more is learned about the operation and subsequent performance of collectors over time, adjustments will likely be made that lead to higher costs.

The above reasons, in concert with others not mentioned, lead us to believe that the cost estimates employed in this study for assumed large-scale (certainly more than today) production and installation of solar systems are valid given present designs and installation practices. It is further believed that these costs are and will remain applicable for the period of analysis used in this study--1978 to 1985.

TABLE A1
STANDARD AIR SYSTEM PARAMETERS[†]

Solar Collectors

Number of glazings	1	
Glass transmissivity (at normal incidence-solar wave length)	0.86	(6% absorption 8% reflection)
Glass absorptance (long wave lengths)	0.98	
Glass emittance	0.89	
Back insulation U-value	0.083	BTU/hr-°F-ft _c ²
Heat capacity	0.5	BTU/°F-ft _c ²
Air flow rate	2	CFM/ft _c ²
Heat transfer effectiveness of collector	4	BTU/hr-°F-ft _c ²
Tilt	Latitude + 10 degrees	
Orientation	Due south	

Collector Air Ducts

Heat loss coefficient (to ambient)	0.1	BTU/hr-°F-ft _c ²
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Thermal Storage

Heat capacity	15	BTU/°F-ft _c ²
Heat loss coefficient (i.e., assuming all heat is lost to heated space)	0	BTU/°F-hr-ft _c ²
Dimensionless rock-bed heat transfer length [§]	10	

Heat Distribution System

Air flow rate	2	CFM/ft _c ²
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Controls

Building maintained at 68°F
Collectors on when advantageous

[†]Values are normalized to one square foot of collector (ft_c²).

[§]The rock-bed length (distance in the direction of flow) is greater than 5 times the relaxation length for heat transfer (15 was used in the model). Physically this means that the bed is at least 12 times as long as the rock diameter. It is important to note that the flow direction is reversed in the rock bed, being in one direction during the charging period and in the opposite direction during discharging.

TABLE A2
STANDARD LIQUID SYSTEM PARAMETERS[†]

Solar Collectors

Number of glazings	1	
Glass transmissivity (at normal incidence)	0.86	(6% absorption, 8% reflection)
Surface absorptance (solar)	0.98	
Surface emittance (IR)	0.89	
Back insulation U-value	0.083	BTU/hr-°F-ft _C ²
Coolant flow rate	20	BTU/hr-°F-ft _C ²
Heat capacity	1	BTU/°F-ft _C ²
Heat transfer coefficient to liquid coolant	30	BTU/°F-ft _C ²
Tilt (from horizontal)	Latitude + 10 degrees	
Orientation	Due south	

Collector Plumbing

Heat loss coefficient (to ambient)	0.04	BTU/hr-°F-ft _C ²
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Heat Exchanger

Heat transfer effectiveness	10	BTU/°F-hr-ft _C ²
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Thermal Storage

Heat capacity	15	BTU/°F-ft _C ²
Heat loss coefficient (i.e., assuming all heat loss is to heated space--this is not ideal since heat lost to the space in summer is not usable)	0.5	(1.8 gallons H ₂ O/ft ² collector)

Heat Distribution System

Design air distribution temperature [§]	120°F
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[†]The values are normalized to one square foot of collector (ft_C²).

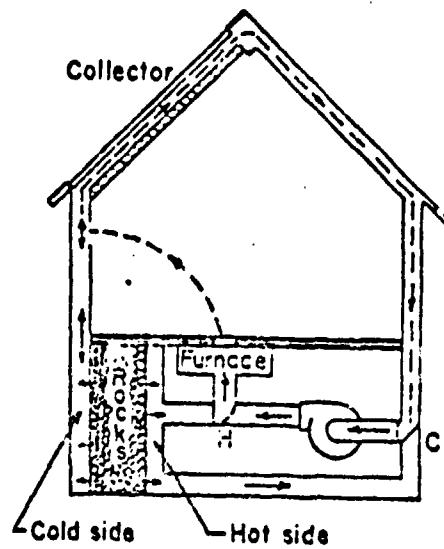
[§]The coil and air circulation are sized to meet the building load with an outside temperature of -2°F with 133°F water and an air flow rate adequate to make up the space heat losses at an air discharge temperature of 120°F. This corresponds to a finned-tube coil effectiveness of 80%.

TABLE A3
SOLAR SYSTEM COST COMPARISONS
(Residential Space Heating)

	<u>Representative Sites</u>				
	<u>Albuquerque New Mexico</u>	<u>Madison Wisconsin</u>	<u>Seattle Washington</u>	<u>East Wareham Massachusetts</u>	<u>Charleston South Carolina</u>
Heating Degree Days	4348	7863	4424	5891	2033
Collector Area 50% Solar (Ft ²)	236	532	408	457	183
Collector- Independent Costs	\$2250	\$2250	\$2250	\$2250	\$2250
Collector- Dependent Costs	\$3186	\$7182	\$5508	\$6170	\$2471
Total System Costs	\$5436	\$9432	\$7758	\$8420	\$4721

TABLE A4
SOLAR SYSTEM COST COMPARISONS
(Domestic Hot Water)

	<u>Representative Sites</u>				
	<u>Albuquerque New Mexico</u>	<u>Madison Wisconsin</u>	<u>Seattle Washington</u>	<u>East Wareham Massachusetts</u>	<u>Charleston South Carolina</u>
Collector Area 85% Solar (Ft ²)	58	95	122	106	78
Collector- Independent Costs	350	350	350	350	350
Collector- Dependent Costs	\$964	\$1564	\$2018	\$1747	\$1283
Total System Costs	\$1314	\$1914	\$2368	\$2097	\$1633



Air Heating / Rock Bed / Forced Air
Collectors / Storage / Distribution

FIGURE A1. SPACE HEATING SYSTEM USING AIR HEATING COLLECTORS

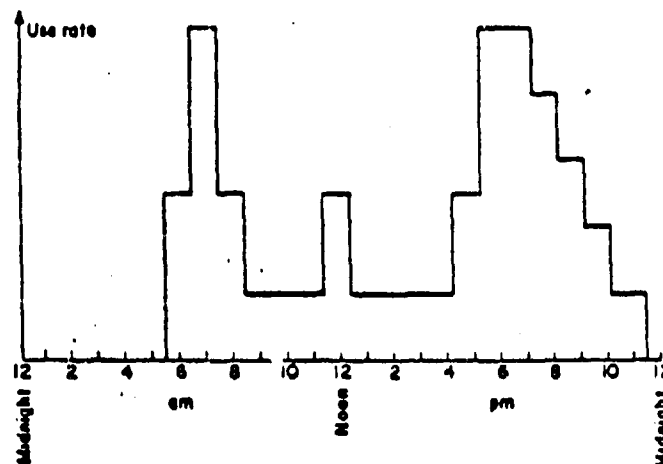


FIGURE A2. ASSUMED USE PROFILE FOR DOMESTIC HOT WATER

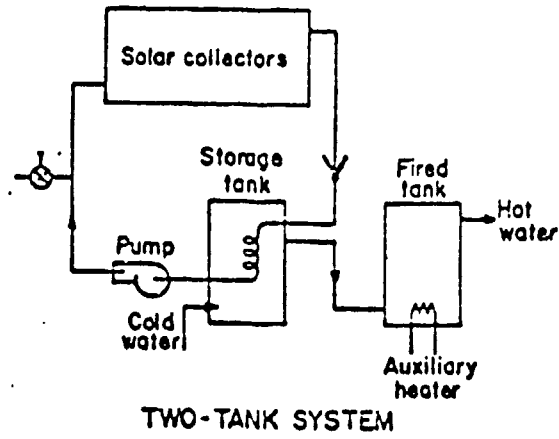


FIGURE A3. DOMESTIC HOT
WATER SCHEMATIC

APPENDIX B

ECONOMIC FEASIBILITY METHODOLOGY[†]

Optimal Sizing and Feasibility Without Incentives

We define the relevant variables as follows:

- r = the real rate of interest[§]
- VC = variable costs associated with each square foot of collector (collector plus storage)
- FC = fixed costs (collector independent)
- P_t = cost of backup heat per 10⁶ BTU (adjusted for furnace and water heater efficiency)
- A = collector area in square feet
- F = fraction of space water heating requirements to be provided by solar energy
- LOAD = 10⁶ BTUs required per year
- t = year
- T = system life (20 or 30 years)
- CR = capital recovery factor =
$$\frac{1}{\sum_{t=0}^T \left(\frac{1}{1+r}\right)^t} = \frac{r}{1 - \left(\frac{1}{1+r}\right)^T}$$
- OP = operation and maintenance expenditures expressed as a percent of total capital investment

From the LASL program,[¶] we know the relationship between collector area and the fraction of solar heat provided, A(F). One would like to size a solar system so that the present discounted value of total life cycle costs (including initial costs, back-up fuel costs, and operation and maintenance charges) are

[†]This appendix is based in part on material developed for and presented in "The Economics of Solar Home Heating," prepared by the same authors for the Joint Economic Committee of Congress (JEC) in March 1977.

[§]Use of the real interest rate as opposed to the nominal rate eliminates the need to forecast inflationary influences and associated price adjustments.

[¶]See Appendix A for a brief description of the performance parameters used by the LASL program to determine the relationship between collector area and fraction of solar heat provided.

minimized. Therefore, one should minimize

$$VC \cdot A(F) + FC + \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t P_t \cdot \text{LOAD} \cdot (1-F) + \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t OP \cdot \left[VC \cdot A(F) + FC \right] \quad (1)$$

with respect to the fraction (F) of solar heat provided.[†] This cost minimization implies that

$$VC \cdot (dA/dF) - \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t P_t \cdot \text{LOAD} + VC \cdot (dA/dF) \cdot OP \cdot \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t = 0, \quad (2)$$

which is the derivative of (1) with respect to F set equal to zero. Factoring and rearranging terms (2) can be restated as

$$VC \cdot (dA/dF) \cdot \left[1 + OP \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t \right] = \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t P_t \cdot \text{LOAD}. \quad (3)$$

Dividing both sides of (3) by the term $\sum_{t=0}^T \left(\frac{1}{1+r} \right)^t$ and noting that

$1 / \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t = CR$, equation (3), with additional manipulation, reduces to

$$\frac{VC \cdot dA}{\text{LOAD} \cdot dF} \cdot [CR + OP] = CR \cdot \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t P_t. \quad (4)$$

If the fixed charge rate (FCR) is defined as $\text{FCR}^{\S} = CR + OP$ and the annualized price (\bar{P}) of the conventional energy source is defined as

[†]We ignore the installation cost of the backup heating system because such a system is required with or without solar heating and so cancels out in making cost comparisons.

[§]CR can be expanded into the notion of FCR, fixed charge rate, relatively easily by including the O & M, taxes, etc. Here we will include only O & M because of the majority of other factors are either generally quite transparent to or not applicable for the average homeowner. By adding O & M expenses (symbol OP), a per cent of total capital expenditures, we will define our FCR as CR + OP. For simplicity we have ignored operating costs in the derivation above.

$$\bar{P} = CR \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t P_t ,$$

the condition for optimal sizing becomes

$$\left[\frac{VC \cdot dA}{LOAD \cdot dF} \right] \cdot FCR = \bar{P} . \quad (5)$$

Equation (5) implies that the solar system will be optimally sized when the marginal cost of obtaining the incremental unit increase in the annual solar fraction (by increasing the collector area) is just equal to the annualized equivalent of the conventional energy price. The A's are known for values of F between .05 and 1.0 in .05 increments from the LASL simulation. We can calculate the change in A (ΔA) for the corresponding change in F where $\Delta F = .05$. Thus, the optimum value of F and consequently the optimal collector area is determined where:

$$\left[\frac{VC \cdot \Delta A}{LOAD \cdot .05} \right] \cdot FCR = \bar{P} \quad (6)$$

Feasibility, however, is not insured by this process. Rather, given an annualized price of energy, collector area will be optimally sized. To check for feasibility one must compute the optimum percentage of space or water heating requirements to be met by solar energy (fraction of solar heat provided, F^*) and the associated collector area (A^*) and using that percentage, calculate the average annualized cost of delivered heat (\bar{P}_h).

The average annualized cost of delivered heat is determined by simply summing the total annualized cost of the optimally sized solar system with the annualized cost of auxiliary energy and dividing this sum by the total BTU heating load of the home.

$$\bar{P}_h = \frac{[VC \cdot A^* + FC] \cdot FCR + \bar{P} \cdot LOAD \cdot (1-F^*)}{LOAD} \quad (7)$$

or

$$\bar{P}_h = \frac{(VC \cdot A^* + FC) \cdot FCR}{LOAD \cdot F^*} \cdot F^* + \bar{P}(1-F^*) \quad (8)$$

which can be interpreted as the weighted sum of the average annualized cost of the solar system alone (\bar{P}_s , the bracketed term in equation 8) and the annualized

cost of the conventional back-up fuel (\bar{P}). Thus,

$$\bar{P}_h = \bar{P}_s \cdot F^* + \bar{P} \cdot (1-F^*), \quad (9)$$

where F^* and $(1-F^*)$ serve as the weights on the solar and conventional costs, respectively. If this annualized cost of delivered energy is less than or equal to the annualized cost of back-up heat ($\bar{P}_h \leq \bar{P}$), then the percentage of space or water heating requirements to be met by solar energy determined above is correct, and therefore solar energy for residential space heating and/or domestic hot water is feasible. If, however, the annualized cost of back-up heat is less than the annualized cost of delivered energy with solar then the solar energy system is not feasible and we set the solar fraction equal to zero. Note that if we are interested in current cost comparisons, the current price of alternative energy can be substituted for \bar{P} .

As F increases from .05 to 1.0 for each site, A increases at an increasing rate, making ΔA a monotonically increasing function. This means that total variable cost ($VC \cdot A$) is also increasing monotonically, whereas FC by definition is constant. We obtain traditional cost curves as depicted in Figure B1, where MC_s and AC_s represent the annualized cost in 10^6 BTUs of a specific solar system. It is important to note, however, that the annualized cost of delivered energy (\bar{P}_h) is what determines feasibility, not \bar{P}_s which is the average annualized cost of solar energy without regard to back-up fuel costs. Remember that \bar{P}_h is given by the weighted average sum formula (9), or again

$$\bar{P}_h = \bar{P}_s \cdot F^* + \bar{P} (1-F^*),$$

where F^* is the optimally determined solar fraction. Thus, as \bar{P} , the annualized price of back-up energy, increases from $\$5.00/10^6$ BTU to $\$9.00/10^6$ BTU, the shape of the \bar{P}_h curve changes as shown in Figure B1, whereas \bar{P}_s remains fixed regardless of the value of \bar{P} . When \bar{P} just equals the minimum value on \bar{P}_s , the minimum of \bar{P}_h exactly coincides. In the figure this occurs when $\bar{P} = \$7.50/10^6$ BTU. For any value of \bar{P} below $\$7.50$, the average annualized cost of delivered heat with solar will be greater than the annualized price of back-up energy ($\bar{P}_h > \bar{P}$), so it would be uneconomical to invest in a solar energy system. However, as \bar{P} rises above $\$7.50$, not only is feasibility obtained ($\bar{P}_h < \bar{P}$) but the optimal system size increases. Thus, the system should be sized to provide approximately 43% solar when $\bar{P} = \$7.50$ and 52% when $\bar{P} = \$9.00$.

Optimal Sizing with Incentives

The above process would ensure an optimally sized system if no incentives existed. However, once the proposed income tax credits are taken into account, the economics of the solar system changes because they effectively involve a reduction in both the average and marginal costs of the system. This implies that for an unchanged value of \bar{P} , it would be worthwhile to increase the collector area and solar fraction beyond the optimal size determined without incentives. A simple example should illustrate this point. Suppose that a refundable income tax credit can be applied to 20% of the total initial solar system cost without an upper limit.[†] The problem then becomes, minimize total life cycle costs [after equation (1)]

$$\begin{aligned} [VC \cdot A(F) + FC] [1 - .20] + \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t P_t \cdot \text{LOAD} (1-F) + \sum_{t=0}^T \left(\frac{1}{1+r} \right)^t OP \\ \cdot [VC \cdot A(F) \cdot FC] \cdot [1 - .20] \end{aligned} \quad (1a)$$

with respect to the solar fraction (F). This yields an optimality condition given by,

$$.8 \left[\frac{VC \cdot dA}{\text{LOAD} \cdot dF} \right] \cdot FCR = \bar{P}. \quad (5a)$$

Upon inspection of equations (5a) and (5), one can see that the marginal cost of the solar system with the incentive is 80% of the marginal cost without such an incentive. The only way to satisfy the condition given by (5a) is to increase $\frac{dA}{dF}$ above its optimal value as given by (5); and such an increase can only

[†]This simplifies the actual structure of the incentives which in the House of Representatives version, for example, are 30% on the first \$2000 and 20% on the next \$8,500 for a maximum credit of \$2,150 on a \$10,000 system; any system cost above \$10,000 does not benefit from additional incentives. The example above is structured for illustrative purposes.

be obtained by sizing the system to meet a higher solar fraction.[†] This is shown in Figure B2 where the marginal cost curves are depicted with and without the incentive.

Figure B2 shows that the marginal cost with incentives (MC_w) is less than the marginal cost without incentives ($MC_{w/o}$) for any given solar fraction F . Since the annualized price of backup energy (\bar{P}) is not affected by the incentives, \bar{P} is depicted as a horizontal line. Sizing the system at the old fraction $F_{w/o}$ under the incentive plan would imply that MC_w (as given by point X) is less than \bar{P} which is less than optimal. One would therefore size the system to provide a solar fraction F_w at which point $MC_w = \bar{P}$, and life cycle costs are at a minimum. The average cost of providing this newly optimized solar fraction is also lower than would be the case without incentives. This implies that economic feasibility is obtained at a lower value of \bar{P} , which with rising energy prices, corresponds to an earlier point in time.

[†] $\frac{dA}{dF}$ can be defined as the inverse of the marginal product of collector area (MP_A), i.e., $\frac{dA}{dF} = \frac{1}{MP_A}$ where MP_A indicates the increase in solar fraction (dF) due to an incremental increase in collector area (dA). Since $\frac{d(MP_A)}{dF} < 0$, the marginal product of collector area becomes smaller as the solar fraction is increased. This implies $\frac{dA}{dF}$ will only increase if F increases.